Quantitative methods of developing escapement goals in the Columbia River Basin: A scientific perspective[1]

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Fish stocks are a renewable resource and must be managed accordingly. Doing so will ensure healthy populations at perpetuity. Under healthy ecosystem circumstances, populations produce more offspring than necessary for replacement[2]. In such healthy systems, the "surplus" adult fish produced are available without causing unduly harmful effects on a population. However, the Columbia River Basin is a special case situation. In most cases, with the exception of a few populations such as the Hanford Reach/Priest Rapids Hatchery spawning aggregate, salmon populations are either declining or are at depressed abundance levels. Setting harvest rates must be made in the context of rebuilding strategies.

Salmon are also a unique species complex, in that the growth areas are quite distinct from the spawning areas. Further, we know with reasonably good precision the value of S, the number of fish returning to the spawning grounds, which is a great advantage[3]. However, we do not know well the number of fish produced by the spawners in their native habitat. We also know that there is tremendous environmental variability affecting survival of salmon. In addition, the causes for decline are more complex than in many other species, and restoration strategies must take this into account. Further, the managers are interested in equitable distribution of mortality among the various anthropogenic sources, such as the hydro system, habitat degradation, and others. Those mortality levels must be estimated and equated to the fishing mortality. The Columbia River is also unique in that such a large fraction of the salmon run is composed of hatchery-reared fish. Undoubtedly, some of these fish spawn in the wild and contribute to some degree to recruitment. How to consider these fish in stock performance is not well established. Finally, an adult taken prior to spawning is [obviously] not going to contribute to recruitment, whereas a juvenile killed by the hydrosystem might have died from natural causes anyway. Terminal fisheries have the additional responsibility of ensuring that sufficient numbers of spawners escape the fishery to contribute to recruitment.

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[1] This document follows into greater technical detail the white paper on supplementation (Talbot, A.J. 2001. Some notes on the role of supplementation in restoration strategies. CRITFC white paper. 7 pages.)

[2] Replacement is defined as the return rate of 1 adult offspring spawner for each spawner in the parental generation, so that the population abundance is stable from one generation to the next.

[3] In ocean fisheries, indeed just about any other type of fish management, the abundance of populations can only be roughly estimated by a variety of sampling and statistical techniques. Knowing the number of spawners eliminates a lot of guesswork.

Below I describe the main quantitative arguments for developing escapement and restoration goals for Columbia River stocks.

Data types, date needs

The most important information needed is the run size, age distribution, catch (number of fish caught and their ages) and fishing effort. If available, additional information can be useful to determine population parameters, such as fecundity, sex ratio, hatchery and wild composition. For a run reconstruction (such as in a cohort model), a great many additional variables (such as size at age, smolt age) and parameters (age-specific mortality, maturation rate, residualism rate) are required. To understand and determine escapement goal, the natural capacity of the spawning and rearing environment must be known within reasonable limits. This information, in conjunction with habitat quality and quantity, and other natural or artificial phenomena (such as migration corridor issues), is necessary to scale the target population levels. In addition to the natural spawning and rearing abundance and habitat capacity, artificial propagation goals must be included.

Measures of yield per spawner

In this text, we'll define S_y as spawners in year y, R_y as recruits in year y, and C_y as the number of fish caught in year y. When a population is exploited such that only the oldest and largest individuals are caught (such as in most in-river salmon fisheries), it is usual that the allowable catch rate will be smaller than it could be because only a small fraction of the population reaches that age as a result of the "natural[4]" mortalities occurring on earlier age groups. On the other hand, it is not a good idea to harvest young fish such that the balance between individual growth and "natural" mortality will result in a reduction in the total biomass[5] of the population. Such an analysis on the mortality caused by the hydro system would be interesting.

Recruitment is determined in a variety of ways. Classically, a recruit is a fish that has reached a size that is vulnerable to fishing. It can be defined as the number of offspring at an early age (such as smolts), but the number of adult fish returning to Bonneville Dam has also been termed recruitment. If the number of spawners of the offspring generation is counted (N_{t+1}) and compared to the parental generation (N_t), then we speak of the spawner-to-spawner ratio, rather than the recruit per spawner ratio.

Intuitively, we understand that as the number of spawner increases so will the number of smolts produced (Figure 1). However, this relationship is dependent on many things.

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[4] In this case, natural mortality is defined as any and all mortality that is not from fishing. It includes mortality from dams as well as from truly natural sources such as resistance to disease.

[5] Biomass is the weight of all the individuals in a population, or, the average weight of an individual fish times the number of fish. In mixed age groups, the calculation is made on an age-by-age basis.

Species have very different productivity. Within species, the shape of the relationship is dependent on habitat quality and capacity, age structure and spawner abundance. The two most common models used to describe the relationship between spawners and recruits are the Beverton/Holt model and the Ricker model (Figure 2). They distinguish themselves in that the Ricker model predicts a decrease in productivity with high spawner abundance that will eventually fall to zero, whereas the Beverton/Holt model predicts a leveling off of productivity. It is often difficult to distinguish between the two models, but the differences are important. If the Ricker model is the correct descriptor of the biological interdependence of spawners and recruits, then managers need to be careful not to overseed the spawning grounds in order to avoid a reduction in productivity. Overseeding is less damaging with a Beverton/Holt model, as the production of smolts does not decrease at high spawner abundance, although the number of smolts produced per female does decrease[6]. The easiest way to distinguish between the applicability of the two models is visually. If it appears that the maximum recruitment is at midlevels of abundance, then the Ricker model may be superior to the Beverton/Holt. There are biological considerations that should be taken into account when selecting a model. For the Beverton/Hold model, growth is density-dependent or density-independent, and mortality is not linked to growth. In the Ricker model, growth is density-dependent and mortality is linked to growth to generate the dome shape. The Beverton/Holt model fits the biological requirements of chinook and coho better than the Ricker model, which in turn may fit better for chum and pinks.

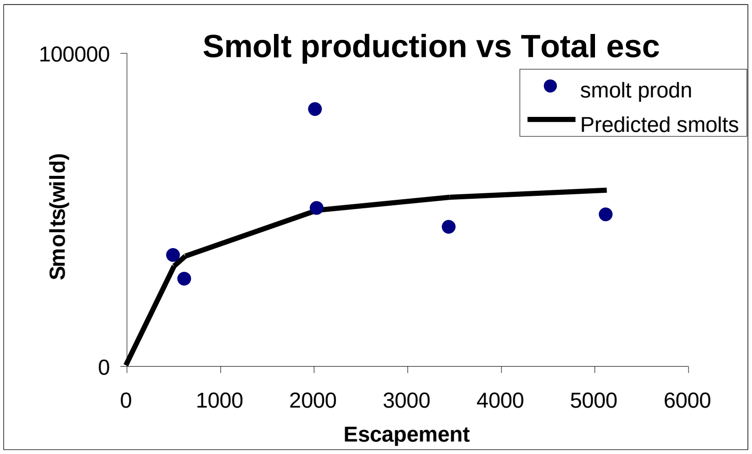

Figure 1: The relationship between the number of spawners and the number of smolts produced (recruits) can be describes statistically

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[6] i.e. some of the spawners are wasted, or the potential fecundity of each female is wasted. However, the population does not suffer from an overabundance of spawners. In the Columbia River Basin, we are far from overseeding any area, and understanding the tail end of the relationship is less critical. Both functions are constrained to start from the origin (0,0), which could make sense (no spawner means no smolts) but is statistically important since it is conceivable that in some ecosystems a small number of spawners may fail to produce any recruits.

Statistically, the more productive a stock is (at a specific number of spawners), the greater the value of the initial slope of the relationship ("alpha", denoted α). Note the top 2 lines in Figure 3. The difference between the two is explained by the slope at the origin (0,0). "*K*" denotes the point at which the maximum number of smolts is produced per spawner. In this example, the maximum number of smolts is obtained with 500 spawners. Fewer or more spawners will result in fewer smolts. Not everyone agrees that there ought to be fewer smolts produced at high numbers of spawners, and if this is the case, the Beverton/Holt model is more appropriate. The consequence of a higher alpha value is that the stock will have a greater growth rate and can rebuild faster. Thus, alpha can be a measure of productivity for a given habitat capacity.

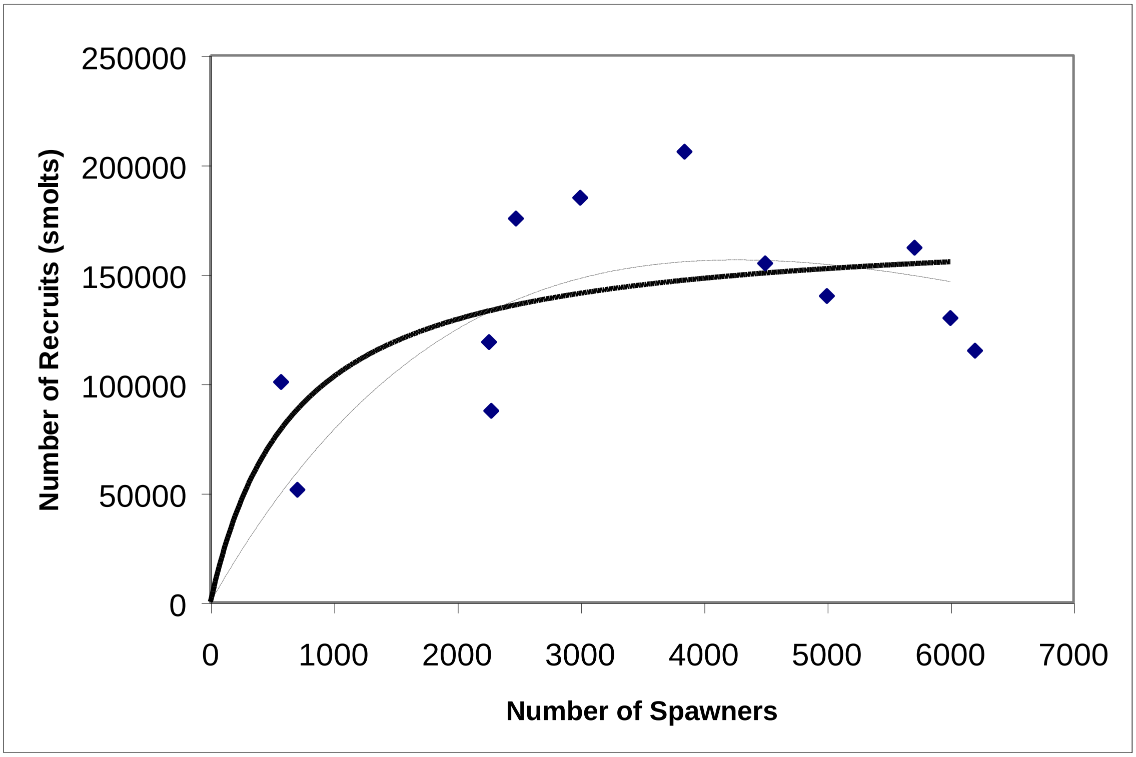

Figure 2: Comparison of Ricker and Beverton/Holt models. Although they appear similar, they make very different predictions at low population levels.

Determining the maximum productivity is a management initiative. The stock is most productive at this point, and thus the maximum harvest rate can be applied to the stock. The Fish Management Department (Stuart Ellis and Rishi Sharma) with the assistance of USFWS (Henry Huen) presented an example using Snake River steelhead. MSY (Maximum Sustainable Yield) is the theoretical point at which the population is most productive[7], and can represent a management goal (minimum escapement or ideal

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[7] Provides the greatest surplus production above the number of spawners required to maintain the population at a stable abundance level. Technically, the stock is most productive at just above the origin (the slope is greatest) and MSY is the point along the curve that produces the greatest yield.

escapement). It was estimated that, historically, the value of MSY was much greater than at present for a given number of spawner (qualitatively equivalent to the difference between alpha of 0.5 and 1.3 in Figure 2). MSY is determined statistically as the point where the number of smolts produced is greatest for a given number of spawners. That number of spawners is known as sMSY.

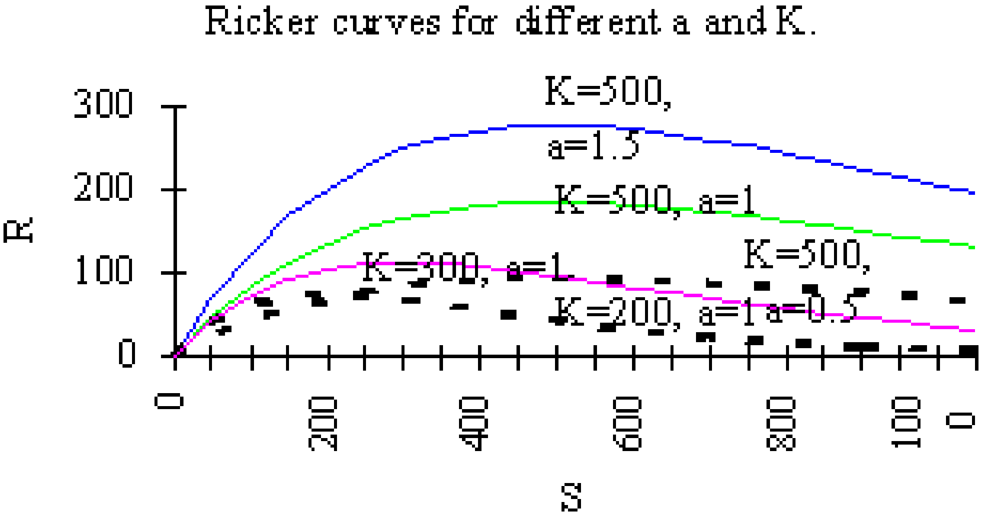

Figure 3: Five Ricker curves. It portrays how the curves change as a function of K (K= 200, 300 and 500) and alpha (0.5, 1, 1.3).

There are several problems with relying on MSY to set fishing quotas. First, the stock/recruit function is an average of all the available data. In reality, the average conditions are never achieved. For example, the recruit per spawner for spring chinook was 0.03:1 in the 1990 broodyear and 6:1 in 2001 in the Wenatchee. Average recruit per spawner would be about 1:1 for this population, thus not providing any surplus for fisheries. Management for MSY would be possible if the productivity of the stock remained above the replacement line. The potential for a significant management error is greater when there is high variation in productivity and the productivity levels are generally below replacement. This is the situation in the Columbia River Basin. Since some years there are “surplus” individuals, it is better to base management on yearly variation rather than the mean for a population. MSY is an interesting concept, but with limited value with stocks at extremely depressed levels. Other issues are too esoteric to get into here but can be discussed.

Hatchery and Wild considerations

Again, the Columbia River Basin is a special case situation. There are far more hatchery fish than wild fish, but all our protection is oriented towards wild fish. It is logical to assume that some of the hatchery fish spawn in the wild, but the routine assumption is that they do not. Data collected over two years in the Snake River, however, indicates that at least 50% of the fish spawning in the wild are hatchery strays. If those fish are not included in the measure of spawners, then the recruit per spawner ratio will be somewhat overestimated (Figure 4). This is important in setting goals, as we'll see later.

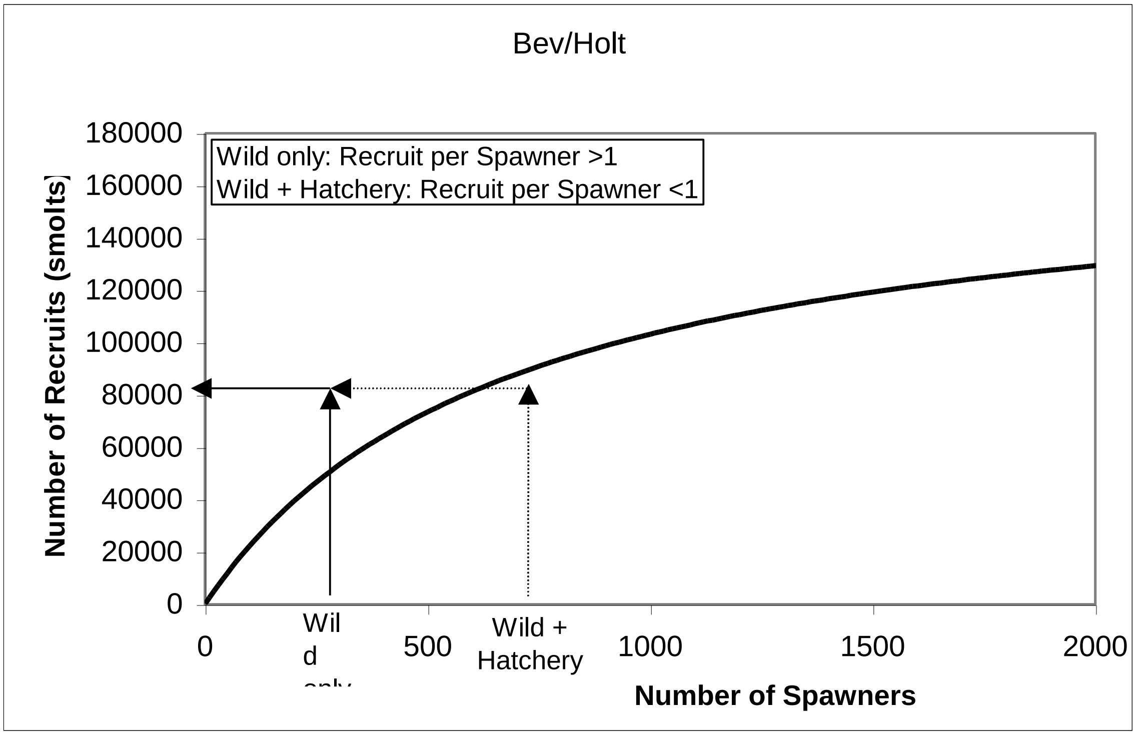

Figure 4: Correctly determining spawner abundance is critical in understnading the status of salmon stocks that are influenced by hatchery populations. If the number of wild fish is used to determine spawner abundance, then in this example, the productivity is above replacement and the population is in relatively good health. However, if the hatchery-reared fish found on the spawning grounds are included, then many more females have produced the observed number of smolts, and the recruit per spawner ratio is poorer (below replacement inthis example).

Figure 4 shows that, without a complete enumeration of the number of spawners in the wild (in this example, hatchery and wild steelhead), the statistical estimate of the population health is biased (too high), leading managers to believe that the problem is smaller than anticipated. Let say for the sake of the argument that the natural spawner to spawner return rate is 0.5:1 (1 female returns for every 2 females spawning). Assuming that the hatchery fish perform as well as the wild fish[8], the natural productivity remains at 0.5:1. However, the additional hatchery fish spawning in the wild will produce a larger run. Thus if 100 wild fish spawned in the wild, 50 fish would return. If an additional 100 hatchery fish spawned in the wild, then from the 200 spawners, 100 would return. Thus, the rate is the same but the run size is greater. However, if the hatchery fish do not perform as well (lets say that a hatchery spawner is only 50% the value of a wild fish, for whatever reason), then while the 100 wild fish do return 50 females, the hatchery component would only return 25, and the combined returns would be 75 females for 200 spawners. In this case, the overall rate of return is reduced but the total number of fish is still greater than the wild fish alone. This is a reason why productivities must be considered in stock management.

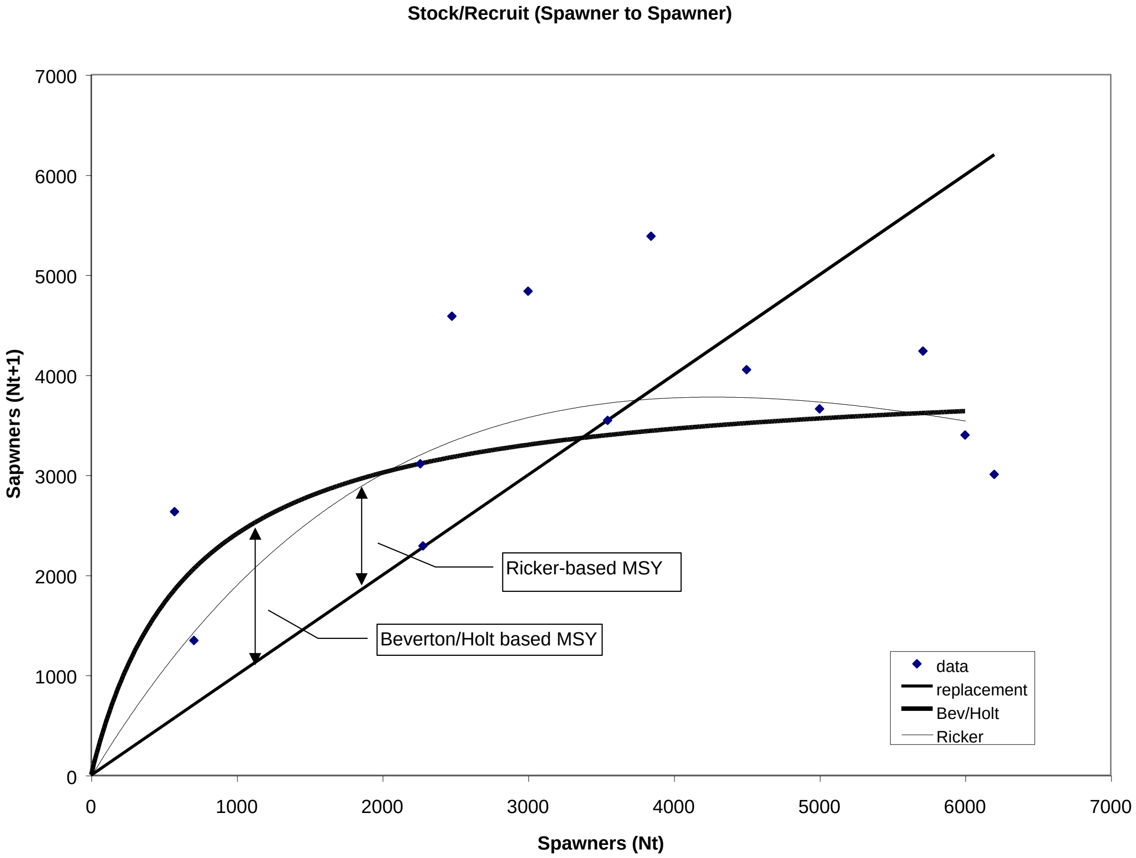

Figure 5: Bev/Holt and Ricker models make very different predictions for the number of spawners that result in the maximum productivity. Decision must be made on both which model fits the data better and what is most likely to be the biological or true relationship in nature.

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[8] I.e. their productivity is the same. This assumption may not be valid for some conventional hatchery programs.

As discussed in the Escapement Goal workshop, the slope of the curves at zero spawners is important and deserves some attention. The highest number of recruits per spawner is predicted at very low population abundance. Because of this reason, escapement goals cannot be based on productivity alone. Second, if the status (abundance) of the population is unknown, productivity could appear high in a population because it is at depressed levels.

Setting Quantitative Goals

The Columbia River Basin is again a special case situation. Because so many populations are in decline, it may be unadvisable to set target fishing based on “surplus” production. One possible alternative is to dissociate the direct link between fishing goals and conservation/rebuilding (spawning) goals. Adult return goals could be back-calculated from the required or desired components in the subbasins (Table 1).

Table 1: Determining the number of adults required (post-recruit) to meet adult fish requirements. An example.

Adult Component	**Number of fish**
Spawning Ground	2000[9]
Anticipated dam Mortality	250
Hatchery (supplementation) broodstock	500
Harvest	1000[10]
Total number of fish needed	3,750

Conservation/restoration goals need to be set based on natural productivity. This is necessary to determine progress towards rebuilding. Further, productivity goals should be set for a number of life history stages (Figure 5). A smolt production goal[11] would assist in determining habitat conservation and restoration initiatives. A goal to the fishery would help determine success of fish production, and a goal set on escapement would assist in determining success in reducing post-smolt mortality.

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[9] Determining the desired number of spawners remains a problem. If we don’t want to use a spawner-recruit function as a predictive tool, how should we come up with the 2000 number? It probably isn’t a good idea to base it on the fresh water carrying capacity. If we did this, we are probably so far below carrying capacity for most stocks we would never fish again. If we are just looking at increasing the productivity of the stocks, how do we know if 1,500 or 2,500 might be more or less or equally compatible with our desire to increase productivity?

[10] If this management goal is used, it still doesn’t quite solve the problem of what happens if (in this case) the forecast is only 2,750 --- Does harvest get zeroed out even if the dams and the terns killed all the juveniles, resulting is a poor overall survival rate.

[11] Possibly some sort of smolt per spawner goal would be useful as well especially if the conservation burden lies with the freshwater habitat managers

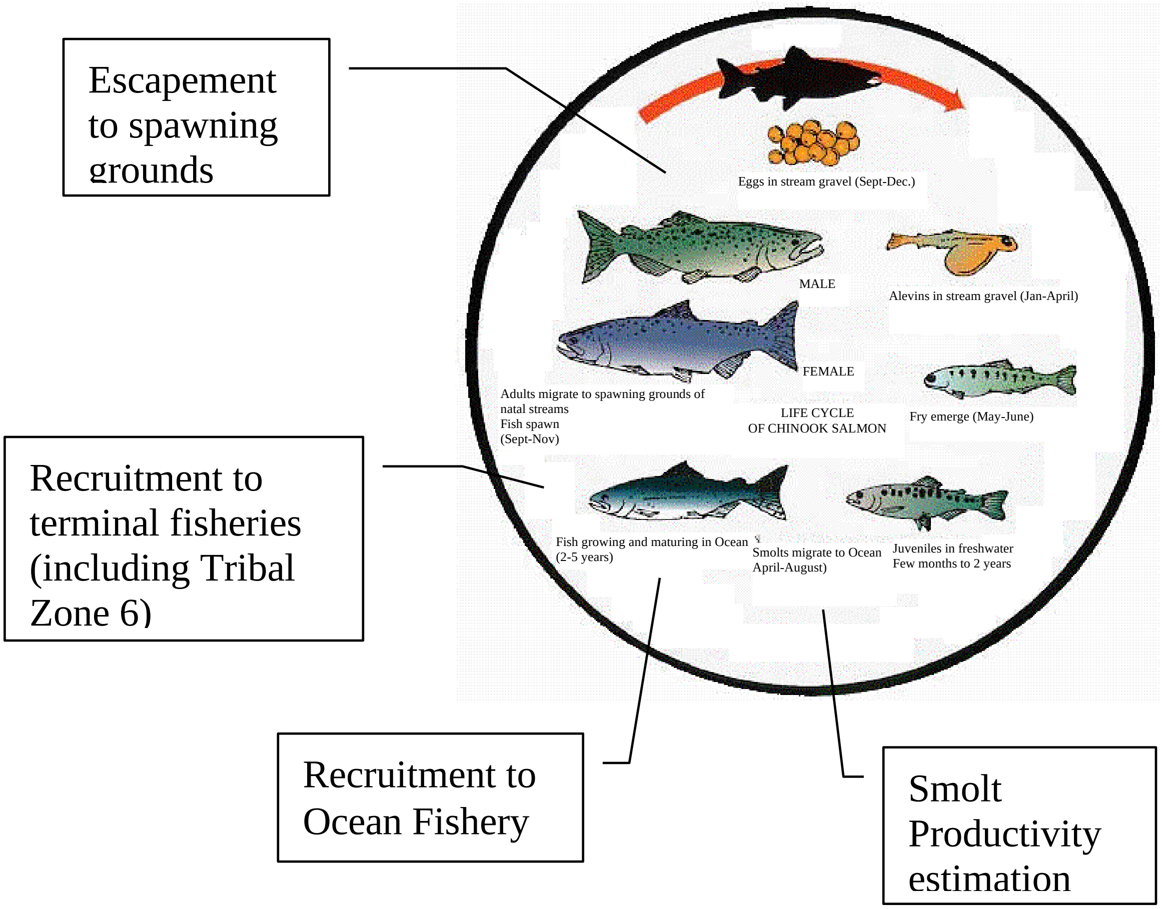

Figure 6: Life cycle of chinook salmon. Critical stages of the life history are shown.

In many locations, the spawner (S_{t+1}) to spawner (S_t) ratio is below replacement, and the population is in decline. Restoration goals are assisted by supplementation in that the population is allowed to rebound from the increased productivity of the hatchery environment.

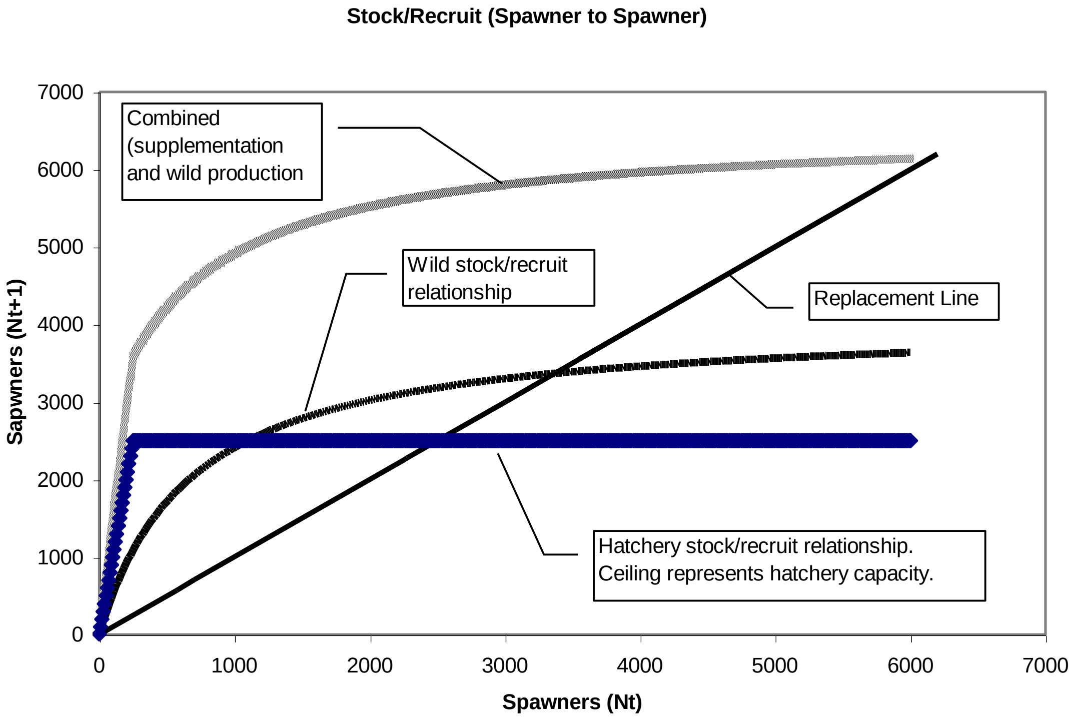

Figure 7: Stock/recruit function showing the benefits (in terms of productivity) of a hatchery program. This is particularly the case when the natural productivity is below the replacement line.

There is considerable year-to-year variation in the recruitment numbers for a given number of spawners. Thus, one must distinguish between the statistical fitting of a stock/recruitment relationship, which averages our conditions in the time series, and the biological variability. It is easier to understand that for each cohort there is a specific stock/recruit function that is dependent on the environmental conditions that the cohort lived through. So, for Mid-Columbia spring chinook, the recruit per spawwner ranged from 0.03 in 1993 (far below replacement) to 6 recently. Thus, the environmental variability affecting recruitment success is larger than the variability in the number of spawners themselves (within a few generations). This has led some to conclude that there is no stock/recruit relationship in salmon. That conclusion would be incorrect since it is quite clear that without spwning stock there can be no recruitment. At the limit, the relationship must pass through zero (0,0). Above that point, some number of spawners will produce some juveniles, although the precise number produced is uncertain because of the extreme environmental variability. There is complete justification in studying the relationship between spawning stock and recruitment, if only to understand the status of a population and the long-term potential of the stock. However, because of environmental variability, these models should not be used to try to predict recruitment.

A simplification of the relationship between stock and "recruitment" (or, production). It is clear that abundance changes from one year to the next, and this variability is of interest.

For example, $B_{y+1} = B_y - Y_y + R_y$, that is, the abundance next year is a function of the current abundance less the fraction of the fish “harvested”[12] plus the recruitment over the present year. Thus, in order to predict trends and future opportunities, changes in productivity must be considered. In setting productivity goals[13] for depressed populations, one should consider using a measure of recruitment per spawner. For example, if stocks are below replacement at present (less that 1:1 ratio of recruits and spawners), then one might set the immediate goal to reach replacement. Ultimate goals should be set at higher levels for sustainability and population health (3 recruits per spawner should be a minimum long-term target, 6:1 probably better (see Appendix A).

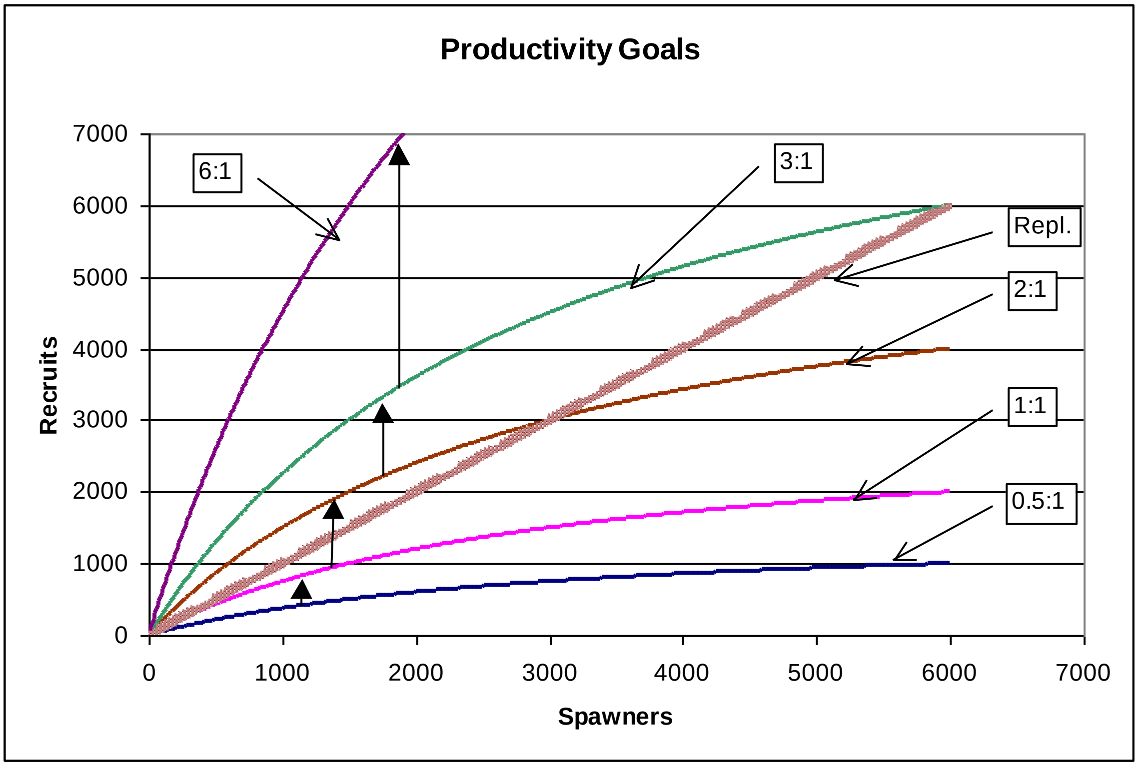

Figure 8: Productivity goals aim to improve the number of recruits produced per spawner in the wild. Progress may be tracked statistically.

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[12] In this case, harvested may include, in addition to the fisheries, dam mortality and other anthropogenic causes of mortality

[13] Besides setting productivity goals, we also need to set harvest management goals. We need to figure out some way, for stocks that are generally in lousy condition, to determine the appropriate number of fish to harvest given a particular adult run size. The development of a method to measure the risk to future production of harvesting a certain number of fish and comparing that to the “benefit” to future production of not harvesting the fish. We need to have some sort of recovery objective and then be able to lay out some alternate harvest management frameworks and be able to explain to them the risks and benefits of choosing different alternatives as far as how they will affect reaching the recovery goals. And also how they fit in with other possible management actions, like supplementation and reducing mortality in other H’s.

In order to progress habitat-based restoration efforts, then, productivity, in association with abundance, must be considered. Cohort modeling could be useful in setting these goals. A table of benchmarks for a specific stream might look as follows:

Table 2: Wenatchee spring chinook productivity

	Observed	Goal
Current adult to adult ratio (5 yr average)	0.442:1	3:1
Abundance	1350	5000
Smolts per female (or egg to smolt survival rate)	(6.97%)	(10%)
Fishing mortality	5.2%	20%
Recruits per female to fishery	0.6:1	2.2:1
Population growth rate	0.84	1.10
Proportion of population that needs to be in the hatchery to meet goals	65%	

For monitoring purposes, such a table could be broken down into the various critical life stages, and abundance at these points plotted against the abundance of the previous life stage (number of spawners vs. egg deposited, egg deposited vs. fry produced, fry vs. smolt, etc.). Using this monitoring method, one could assess where the greatest losses or fish are occurring.

The Role of Supplementation

As described in the CRITFC technical paper on supplementation (see appendix), the role of supplementation, from a conservation perspective, is to provide protection for a stock that is declining because of unfavorable environmental conditions. For example, it is shown in Figure 9 that, under good environmental conditions (sediment load very low), the hatchery contribution may not have a great affect on overall productivity. However, in situation where survival in the streams is hampered by poor habitat, supplementation can play an important role is population sustainability.

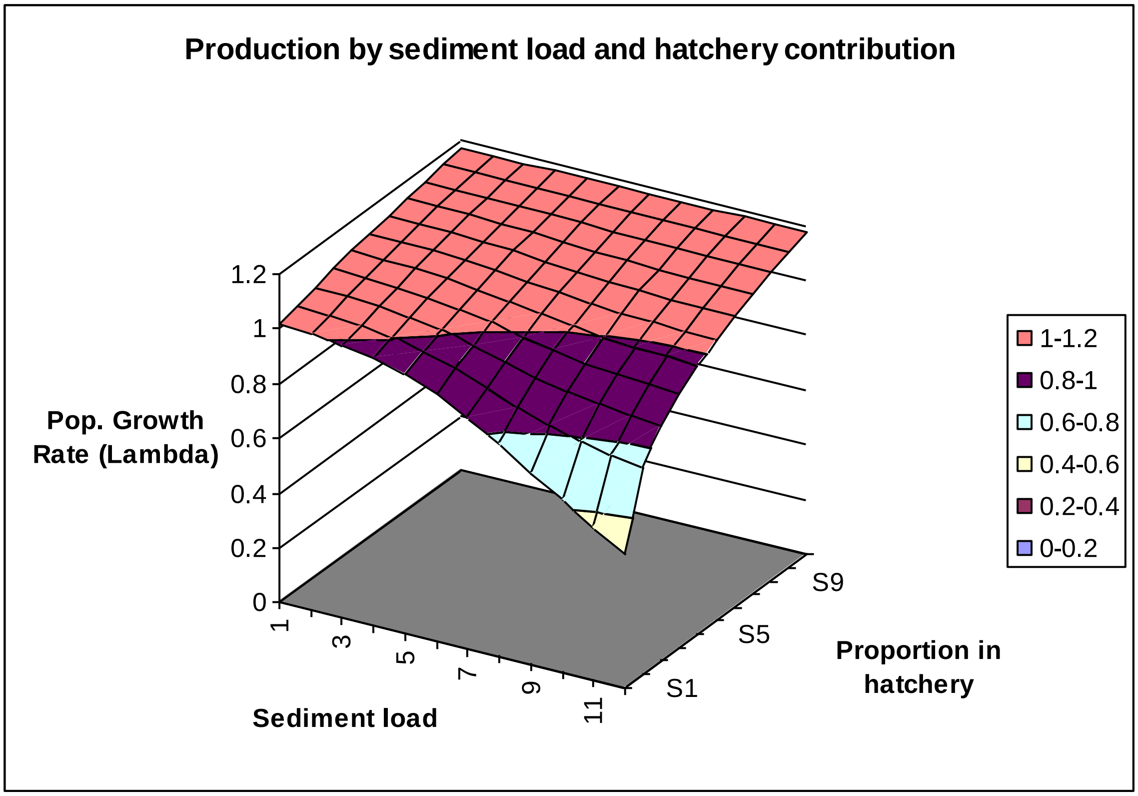

Figure 9: Surface plot of population growth rate against sediment load in a stream and proportion of the run in the hatchery (supplementation). Methow River spring chinook cohort analysis was used as an example. For a population to exceed replacement (population growth above 1), under the current hydrosystem configuration, sediment loads must be very low so that egg to emergence survival is high. Until environmental conditions can be improved, supplementation may play an important role in preventing extirpation.

Appendix A

The determination of population health includes many factors (please refer to white paper on supplementation[14]), some genetic, some ecological. Studies aiming to evaluate census or effective population sizes, identify recent bottlenecks, measure ongoing inbreeding and variability in reproductive success, estimate the effect of habitat fragmentation and continued decline in wild populations on gene flow, specify the evolutionary status of endangered populations and their possible hybridization with relatives from other populations, identify evolutionary significant units for conservation, assign the origin of immigrating individuals, design optimal re-introduction strategies and breeding programs, or predict the fate of released putatively "genetically modified" individuals are all necessary. The impact of bottleneck on viability of populations depends largely on variability in reproductive success. Using the adult to adult return rates as surrogate for reproductive success, and assuming that they are statistically distributed in accordance with the Poisson distribution among individuals in a population, we can estimate critical conservation parameters for declining and rebuilding populations (see Figure 10 below). For a population at replacement, the loss of family lineages per generation is 38%, whereas it is only 13% for populations with a 2:1 adult-to-adult return rate. However, for a return rate of 50%, the complete loss of families is over 60% per generation. In such circumstances, supplementation hatcheries can play a major role in conserving genetic variability necessary for population health.

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[14] **Talbot, A.J. 2001. Some notes on the role of supplementation in restoration strategies. CRITFC white paper.**

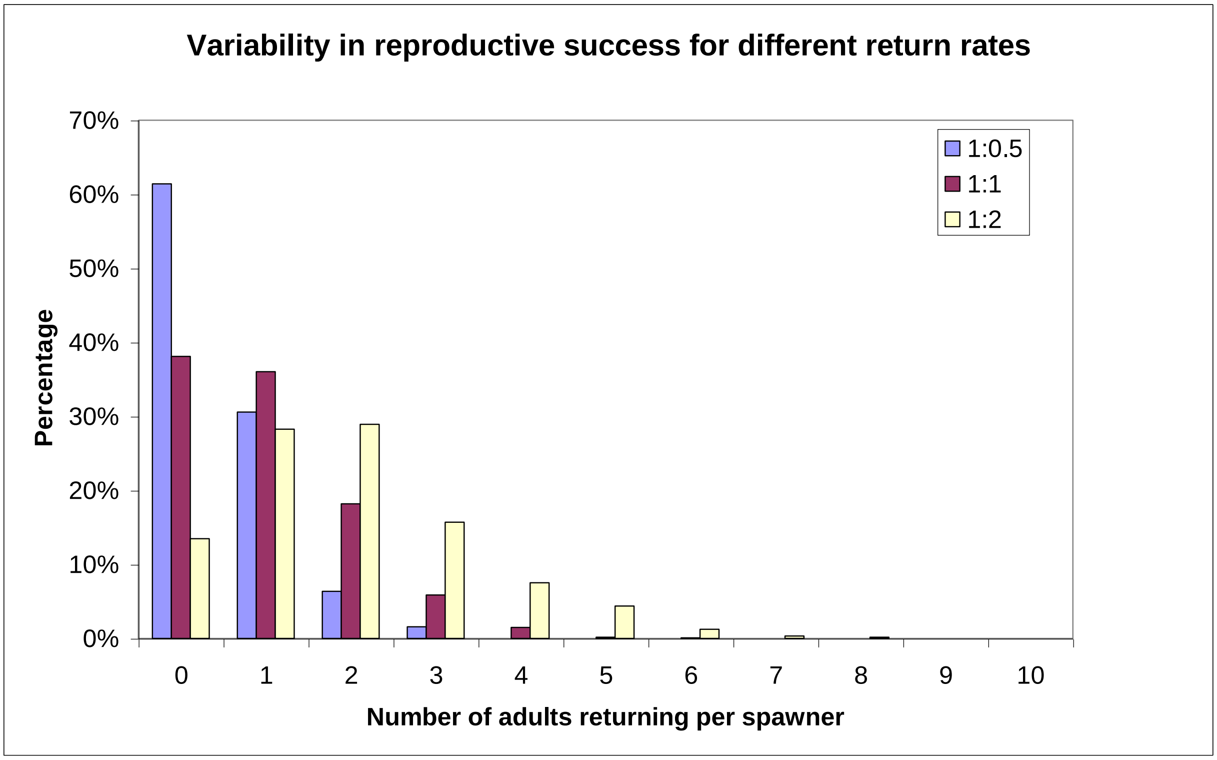

Figure 10: Variability in reproductive success for different return rates. The Methow wild population is approximately 0.5 returning adult for every spawner. The hatcheries are returning about 3.5 fish per spawner, based on individual family values provided by WDFW.