SOUTHWEST FISHERIES SCIENCE CENTER

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# ESTIMATING ESCAPEMENT OF THE SACRAMENTO RIVER WINTER-RUN CHINOOK: A REVIEW OF METHODS

Edited by

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ADMINISTRATIVE REPORT T-97-02

# Estimating escapement of the Sacramento River winter-run chinook: a review of methods

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# Abstract

Methods for estimating the size of Sacramento River winter chinook populations are reviewed. No single method is expected to work well because winter chinook are rare, and are widely distributed in space and time during all phases of their life cycle. Methods for concentrating chinook are expected to have unacceptable impacts on adults or juveniles. A suite of population size measures should be used, including ladder counts at Red Bluff Diversion Dam, aerial surveys of spawning grounds, mark-recapture studies of carcasses, smolt production estimates, and use of microsatellite DNA markers to estimate population sizes from the ocean fishery. Such a multi-pronged approach provides independent estimates of population size as well as complimentary information on winter chinook life history. A consideration of environmental variability, sampling precision, and likely recovery rates suggests that at least ten years of monitoring will be required before the effects of restoration measures will be detectable.

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# 1 Introduction

Populations of endangered species must be monitored in order to gauge the effectiveness of recovery actions or evaluate the need for additional protective measures. In the Sacramento River, the winter-run race of chinook salmon, *Oncorhynchus tshwaytscha*, is in danger of extinction due to the effects of dams, water diversions, pollution, ocean harvest, and river flow reductions.

A variety of management plans are underway and being developed in order to restore the winter-run chinook. Programs include releases from Shasta Dam to keep water temperatures below lethal levels, raising the gates at Red Bluff Diversion Dam (RBDD) to improve fish passage, imposing size and season restrictions on the ocean fishery, and limiting water exports from the Delta.

These management activities are expensive, and it is desirable to know how effective they are. Effectiveness can be judged by some benchmark related to winter-run abundance at some life stage. Currently the focus is on spawning escapement, although the number of juvenile outmigrants might be as good or better measure of population size. Adult escapement must be known, however, since the escapement estimate is used to calculate pre-season juvenile take limits for Delta pumps. These limits must be set before winter chinook outmigration begins, so direct measurements of juvenile abundance cannot be used for this purpose. From an overall monitoring perspective, adult and juvenile abundance estimates are most valuable in combination, since together they provide insight on river and ocean conditions.

Determining spawning escapement is not easy, and current estimates are imprecise. For the last decade, escapement has been estimated from the numbers of winter run using fish ladders at RBDD. Fish are forced to use the ladders after 15 May, when on average, 85% of the run has passed. This subsampling introduces errors, which are made worse by the fact that run timing varies substantially from year to year. This report presents an overview of the past and current counting techniques, a review of alternative techniques, recommendations, and some analysis of potential counting precisions and the power that this would give to detect various rates of recovery.

# 2 History

Between 1966 and 1986, all salmonids migrating beyond Red Bluff were forced to use fish ladders to pass the Red Bluff Diversion Dam. The dam is used to generate a head that allows river water to be diverted into the adjacent Corning and Tehama-Colusa canals. A series of panels is lowered into the water, and most of the flow passes under these panels, or gates. The remaining flow passes over the fish ladders. Fish swim up the ladders and can be observed directly or by video through windows on one side of the ladder's top step.

RBDD causes several problems for salmon migration when the gates are down. The dam passes water under the gates at too high a velocity for fish to swim against. The flow down the ladders is small ($\sim$300 cfs) relative to the flow under the gates (10,000+ cfs), causing migration delays as the adults search for a way upstream. Salmon orient with the flow; the hydraulic effect of the underflow gates results in impressive upstream flows in the 10 to 20 m below the gates. Salmon can be seen swimming in a downstream direction at the tails of the hydraulics.

Delays are undesirable since the salmon have limited energy reserves that must carry them through migration, redd construction, and spawning. Perhaps a more important problem is for the juveniles. The juveniles pass under the gates and into a highly turbulent zone behind the dam. The turbulence is disorienting to the juveniles, making them susceptible to predation. Squawfish concentrate immediately downstream of the turbulent zone when the gates are in, apparently to take advantage of this artificial situation.

In 1993, the National Marine Fisheries Service (NMFS) mandated that the gates be raised between 1 November and 31 April, allowing most winter-run chinook adults and juveniles to pass RBDD without using the ladders. Escapement is now estimated from counts made after 31 April, when roughly 85% of the winter run has passed. Fish swim up the permanent ladders located at the sides of the dam, and pass by Plexiglas [1] windows monitored by color video cameras. A removable ladder is placed in the center of the dam, and fish are observed by video camera from above. The video signals are monitored by the United States Fish and Wildlife Service (USFWS) personnel during daylight hours. Occasionally, video recordings are made at night to estimate the proportion of fish passing at night; this proportion is usually less than 5%. Some fish are trapped at the east-bank ladder and assessed for coloration and ripeness. This is done to distinguish between winter- and spring-run fish, and a correction factor is calculated to convert total passage to winter-run passage.

There are several sources of inaccuracy and imprecision in this escapement estimation technique. The obvious problem comes from the small sample size–only 15% of the fish are counted, and total counts are expanded accordingly. Similarly, only 1/3 of the fish that are

[1] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA

counted can be identified as winter run, and some fish pass at night. These errors can be thought of as random sampling errors. More serious errors come from the non-uniform distribution of the run with time: only the tail is counted, so if the run is late, escapement is overestimated substantially. Additionally, there is probably a systematic bias related to run timing since the 15% comes from historic counts and the timing of the run is known to be altered when the gates at RBDD are down.

In 1993, meetings were held to address the problem of estimating fish passage at RBDD, and a variety of approaches were identified and evaluated (Hiebert and Mueller, 1993). The approaches focused on techniques that could be applied at RBDD. It is possible that other sites might be more suitable, because the river at RBDD is broad, shallow and sometimes turbid. Possible techniques include the following:

1. Video arrays
2. Hydroacoustic arrays
3. LIDAR (Light Detection and Ranging)
4. Inductance
5. Modulated infrared
6. Shadow graphing

No single technique was identified as ideal. A combination of video and acoustic techniques was deemed reasonable, and LIDAR was found to be a promising but unproven technology. Any technique must be able to meet the technical and logistical challenges posed by the situation in the Sacramento River.

Improving estimates of winter-run population size will not be easy. It is a needle-in-the-haystack problem, with the added difficulty of lots of needle-like things mixed in with the hay as well. Basically, we need to count a few hundred to a few thousand fish in a medium-size, often turbid river that contains substantial numbers of other chinook races, steelhead, suckers, squawfish, shad and detritus. Winter-run chinook are dispersed in space and time. Direct observation at fish ladders gets around the problem of dispersion in space by forcing the fish through very small defined spaces where they can be differentiated visually from other fishes, including chinook from other runs. Unfortunately, it appears that any scheme that forces spawners into a small area will have adverse effects on the spawners and/or on the juveniles.

# 3 Review of Ways to Estimate Winter-Run Chinook Abundance

We can divide possible methods of monitoring winter-run chinook into three categories: counts of upstream migrants, counts of spawners, and counts of juveniles migrating downstream. Cousens et al. (1982) presented a comprehensive review salmon escapement estimation techniques used in the Pacific Northwest.

## 3.1 Enumeration During Migration

A direct way of estimating spawning escapement is to count salmon as they pass by a fixed point on the river located below the spawning areas. The method must be able to distinguish between types of fish, because Sacramento squawfish also migrate upriver in the winter and spring. Up to 9,000 squawfish per month were observed passing RBDD in the late 1970s (Bureau of Reclamation, 1983).

### 3.1.1 Acoustic Methods

Hydroacoustics have been used on several rivers to estimate spawning escapement. Several approaches are possible, including side-scan and fan-scan sonar (Bendix), Doppler sonar (Biosonics), and hydroacoustic imaging (Scripps Institution of Oceanography).

There are a variety of pitfalls, some of which can be avoided by proper placement of the equipment. Problems include milling of fish, shadowing and reverberation by objects on the river bed, and distinguishing salmon from a field of other fish. Cousens et al. (1982) stated that accuracy of side-scan sonar systems declines at escapement rates of less than 3,000 fish per day, several orders of magnitude greater than the expected peak migration rate of recent winter chinook populations.

Jaffe and co-workers at Scripps Institution of Oceanography are developing acoustic imaging systems for studying the three-dimensional motions of zooplankton in the ocean (McGehee and Jaffe, 1996; Jaffe et al., 1995). Their systems use arrays of transmitters and receivers oriented perpendicularly. Each transmitter sounds sequentially, and echos are picked up by all of the receivers. Typically, 8 transmitters and receivers are used, giving 64 beams. These systems are capable of determining the size and velocity of organisms with much greater accuracy than the standard dual- or split-beam systems. This system has not yet been applied to fish in rivers.

While hydroacoustic techniques might be worth testing for winter chinook, and would provide useful information for fall chinook, the problems of distinguishing between winter chinook and other fishes might be intractable. A useful hydroacoustic system would cost between $100,000 and $1,000,000 depending on configuration and placement.

### 3.1.2 In-River Video Methods

When NMFS considered the problem of estimating winter chinook spawning in 1993, video arrays were identified as potentially useful (Hiebert and Mueller, 1993). The idea is to place arrays of video cameras in the gates at RBDD; 24 cameras could provide 50% coverage when the river is 2 m deep. A major problem not considered by Hiebert and Mueller is that during freshets, the water level and turbidity will be considerably higher. This means that unknown numbers of chinook will pass undetected. Also, video requires artificial illumination at night (and is aided by it during the day), which would likely cause migration delays.

### 3.1.3 Weirs

An obvious approach to estimating escapement is to build a weir, forcing the spawners to use an easily passed yet easily monitored point. This is probably more difficult than it would seem at first glance, since the smaller the weir, the higher the velocity, and the more difficult time the fish will have passing it. On the other hand, larger passages are more difficult to monitor. Finally, what might work well during normal flows might not work at all during freshets.

A weir might be more practical if placed in a minor channel and there was a barrier in the main channel. Palmisano and Burger (1988) used a portable electric barrier to divert migrating adult chinook from the main channel to a side channel of the Killey River in Alaska. They placed a weir and fish trap on the side channel. They used this system to obtain fish for a mark-recapture study of spawning escapement. The electric barrier was found to kill some fish, and although mortality could be drastically reduced by using direct current and proper arrangement of electrodes, any mortality of winter-run adults would be unacceptable.

It makes much more sense to use a fence to divert salmon to a counting channel. It would be difficult to make a fence that could resist flood waters, and to keep the fence clean of debris. A fence would be much better than a dam because juveniles could easily pass through it, while adults could be directed to the counting weir where they could be counted and trapped if required. Knowledgeable engineers would have to be consulted to determine the feasability and cost of such a system.

### 3.1.4 LIDAR

The Hiebert and Mueller memo discussed the use of systems for counting winter-run chinook. Laser light can be used to detect targets and acquire spectral information from them which can be used to identify the object, although this has not been done in situations like that in the Sacramento River. This technique merits further consideration. In 1996, USFWS sponsored a study to see if spectral reflectance measurements could be useful under field conditions at RBDD. Results are not yet available.

### 3.1.5 Modulated Infrared (MIR)

Arrays of modulated infrared emitters and detectors could be used to detect the size and travel direction of objects in water, and thus have the potential to count fish swimming upstream. Such a system would not be able to distinguish between chinook runs and would not work during episodes of high turbidity. Furthermore, infrared light has very limited ability to transmit through water, and several arrays would have to be placed within each gate at RBDD to get full coverage. The arrays would probably need to be removed from the river during high-flow episodes to prevent damage, and they would be ineffective during such events in any case due to high turbidity.

### 3.1.6 Shadow Graphing

Shadow graphing uses visible light sources in a way similar to the MIR system, and would be subject to all of the same problems as MIR, with the additional problems associated with artificial illumination. A video array would be less expensive and provide more information.

## 3.2 Surveys of Spawning Reaches

### 3.2.1 In-Water Surveys

Salmonid spawning populations can be censused by direct visual observation (Tschaplinski and Hyatt, 1991), either with SCUBA, by snorkeling, or by walking the banks. The best method depends on the water depth, clarity, and current velocity. Dives on redds are performed occasionally in the Sacramento. In general, however, it would be impractical to survey all the spawning reaches even under ideal conditions, and in the winter, conditions are often difficult.

Swan (1989) described a SCUBA survey of deep-water spawning by chinook in the Hanford reach of the Columbia River. The Columbia presents more difficult physical conditions than the Sacramento, with on order of 60 times greater discharge. The divers rode a sled that was towed by a boat on cross-channel transects. The location of the sled was determined with a laser locating system, allowing the locations of redds to be accurately determined. Extrapolating from 8 transect lines spread over 84 km of river, Swan estimated that there were almost 5,000 redds during the peak spawning period; total escapement was estimated to be 38,000 females.

On typical transects reported in Swan (1989), about 30 redds were observed, roughly equivalent to the number observed for the entire upper Sacramento during a season of helicopter surveys. If the same transect approach was used on the Sacramento, probably no redds would be observed. It is hard to imagine how 90+ km of river could be surveyed by SCUBA to get a meaningful run-size estimate. However, information on the depth distribution of spawners would be valuable if combined with aerial survey data, as discussed below.

### 3.2.2 Aerial Surveys

The distribution of winter-run redds in the upper Sacramento is currently measured by Frank Fisher of the California Department of Fish and Game (CDFG) in Red Bluff. Visual observations are made from a helicopter, and the locations of redds are noted on maps. Surveys are made once per week. No effort is made to estimate abundance of spawners or redds, because the surveys are designed only to determine how far down stream spawning is occuring. This information is used in the management of in-river water temperature. Fall-run redds are counted using aerial photography from a fixed wing aircraft.

The difficulty in getting quantitative estimates of spawning is that visibility is variable and some fish spawn in areas that are too deep to be observed from the air. Accuracy and precision of aerial counts is also probably highly dependent on the observer. Fisher may soon retire. In a comparison of a variety of techniques, Tschaplinski and Hyatt (1991) found that aerial surveys underestimated spawner abundance by about a factor of ten compared to various mark-recapture and in-stream survey methods. On the Sacramento River, a similar discrepancy between redd counts and population estimates made from fish passage at RBDD is observed. Overall, aerial redd counts provide a useful independent measure that can be used as an index of escapement, if not a direct escapement estimate. Helicopter time costs about $20,000 per year.

### 3.2.3 Mark-Recapture

Several mark-recapture designs have been used to estimate spawning escapement of salmonids, including the following:

- Tag live fish; observe live fish (Tschaplinski and Hyatt, 1991; Palmisano and Burger, 1988).
- Tag live fish; observe dead fish (Bradford et al., 1995).
- Tag dead fish; observe dead fish (Shardlow et al., 1986; Sykes and Botsford, 1986).
- Tag dead hatchery fish; add to river; observe dead fish (Shardlow et al., 1986).

Each of these strategies and its applicability to winter-run chinook is discussed below. Mark-recapture studies are based on several assumptions that can be difficult to satisfy. These assumptions include (1) random application and/or recovery of tags, i.e., sampling efforts distributed evenly over the duration of the run; (2) tagging does not affect the fish in any way.

*Tag live, observe live*

In this approach, fish must be captured during their migration. Typically, tags (discs or streamers coded by color and/or serial number) are applied to the fish, which are then released back to the river. Subsequently, surveys are conducted to see what proportion of spawners carry tags. Because the spawning season is much longer than the time spent on the spawning grounds by a fish, multiple tag applications and recovery surveys must be made. Survey techniques include visual counts, electrofishing, and netting. Tschaplinski and Hyatt (1991) describe a variety of approaches using multiple mark-recaptures with visual surveys. The techniques can give reliable results when the necessary assumptions are met.

An obvious problem with applying this approach to winter run is capturing and tagging the fish. This is probably only possible at RBDD when the gates are down and the fish trap is running. When the run is small, for example 200 fish, only 5% of the run (about 10 fish) would be expected to be available for tagging. Only a few of these would be recovered at most, so estimates would be very unreliable estimates.

*Tag live, observe dead*

Bradford et al. (1995) reported the results of several mark-recapture studies of sockeye salmon in the Fraser River watershed. They performed experiments to test the assumptions of the Peterson method, and found that mark-recapture estimates overestimated escapement by an unknown amount due to tag loss and perhaps tagging mortality. This technique would not currently work well for winter chinook because too few live fish could be tagged.

*Tag dead, observe dead*

In this technique, natural carcasses are found, tagged, and returned to the river. CDFG has used this technique to estimate fall chinook run size for some time on Bogus Creek (Boydstun, 1994), and applied it to Sacramento River winter chinook in 1996 (Bill Snider, CDFG, personal communication). CDFG uses a modified Schaefer mark-recapture model (Ricker, 1975; Boydstun, 1994) to estimate the spawning population. Carcass surveys are conducted each week using two boats. Carcasses are assessed for tags, and if they are untagged, they are tagged and returned to the river. Boats survey the opposite side of the river the following week so that workers do not know where tagged fish were placed. The idea is that the tagged carcasses serve to mark the population of fish that die during the week between tagging and recovery seven days later. The Schaefer model requires that carcasses be available for tagging in each tagging period, and that some tagged carcasses be recovered during recovery periods. Neither of these requirements were met in the 1996 experiment. These problems could be overcome by adding tagged carcasses obtained from hatcheries.

*External additions of marked carcasses*

Shardlow et al. (1986) marked carcasses obtained from a hatchery and released them into a river; the recovery rate of the marked carcasses was then used to calibrate recoveries of wild carcasses. This approach is perhaps the most attractive for application to winter run. Carcasses could be obtained from the Coleman hatchery, tagged with external neutral color, numerically coded tags, and released randomly into the river. Many carcasses could be added, insuring that enough tags would be recovered to get a meaningful population estimate. Care in carcass selection would be necessary since carcass size has a strong effect on the likelihood of recovery (bigger carcasses are more likely to be found). Carcasses from the fall run could perhaps be kept frozen for later use.

In an ideal study, carcasses would be released at regular intervals in a pattern that mimics the distribution of spawners. Surveyors who do not know the timing, location, or magnitude of carcass additions would perform routine river surveys, focusing on shallow, slow water areas and deep holes. Carcasses would be measured, tags removed if present, and cut in half to prevent recounting. This scheme could be implemented with the existing work force, but would require acquisition and storage of a few hundred carcasses.

### 3.2.4 Use Mark-Recapture Results to Estimate the Expansion Factor for RBDD Counts

It may be possible to combine the RBDD counts and the mark-recapture results to provide a composite estimate. The problem with counts at RBDD is that they depend on an estimate of the run timing. This estimate is used to estimate the number of fish passing after gates are removed from the number counted. We know from the historic counts made when RBDD gates were in the river year-round that run timing is not constant between years. The mark-recapture data gives weekly estimates of the number of spawners. If we can estimate the time lag between RBDD passage and death, we can use the mark-recapture data to estimate the fraction of the run that passed RBDD before the gates were removed. The "hybrid" estimate would minimize the problem of using constant run timing in correcting RBDD counts, and minimize the bias in mark-recapture estimates that might exist due to invalidation of model assumptions (zero recoveries, portions of run unavailable to sampling).

The time lag could be directly estimated by marking some of the winter chinook as they are handled at the RBDD fish trap. The mark would have to be unique, durable (carcasses are sometimes partially decomposed), and safe. No such mark exists. It would be possible to take a small fin punch from trapped fish for DNA fingerprinting (restriction enzyme polymorphisms). Punches would also be collected from carcasses. DNA fingerprints could then be compared and matches used to estimate the time lag. Alternatively, the lag could be estimated from behavioral data (swimming speed, distance between RBDD and spawning sites, time between nest site selection and death).

## 3.3 Alternative Population Size Estimates

### 3.3.1 Smolt Production

Monitoring the changes in smolt production or outmigration of juvenile chinook is a valid alternative to determining spawning escapement, and has the potential advantage of more strongly reflecting changes in river conditions and ignoring changes in ocean conditions. In any case, it would be complimentary to spawning escapement estimates.

Currently, several screw traps are operated at RBDD. Screw traps are conical screens mounted on pontoons, and they sample the river surface. Water enters the mouth of the cone and impinges on vanes, causing the cone to rotate, preventing small fish from escaping. The fish end up in a live box at the end of the trap. The traps must be cleaned out periodically and are vulnerable to debris. Fish can potentially avoid entering the trap, and bigger fish avoid traps more easily. Catch rate has been found to be highest at night, consistent with visual avoidance. In spite of these difficulties, a well-designed screw trapping program could provide a valuable abundance index for juvenile winter run.

It might be desirable to use screw traps combined with a video camera; rather than capture fish in a live box, fish could be allowed to pass out of the screw trap through an acrylic tunnel monitored by a video camera. The advantages of such an approach would be reduction of handling stress and predation within the live box, and creation of a permanent record. Computer-aided analysis has been used to count fish and determine their length and body depth (Irvine et al., 1991).

There is an ongoing and extensive beach seining effort being conducted by a variety of agencies and offices along the entire Sacramento River. This work is part of the Interagency Ecological Program (IEP). Currently, the emphasis is on migration timing, and there is little coordination of sampling effort or data reporting. The data being collected could potentially be used to develop a winter-run smolt production index independent of the screw traps.

It is also possible to count small fishes with hydroacoustics. If the transducers are tuned appropriately, the size of the fish can be determined, making it potentially possible to distinguish between runs, at least on the upper river where there are distinct size differences between runs. Like using hydroacoustics for counting adults, there is the problem of counting relatively rare fish against a noisy background of debris and other fishes.

### 3.3.2 Ocean Adults

Workers at Bodega Marine Laboratory have developed a suite of microsatellite probes that are nearly specific to winter chinook. These probes could be applied to samples from the ocean fishery catch to determine the contribution of winter chinook to total catch, although extensive sampling of the catch would be required because winter chinook are so rare. Fisheries models could then be used to estimate the population size of winter chinook. This information would be extremely valuable, since it would allow the spawning run to be forecast. The estimates of fishing mortality rate from these studies would be useful in their own right.

# 4 Recommendations

I recommend that several monitoring techniques be applied. Each one gives somewhat different complimentary information. The recommended techniques include the following:

- Fish passage at RBDD.
- Carcass mark-recapture with externally-supplied carcasses.
- Aerial surveys of spawning grounds.
- Counts of outmigrating juveniles.
- Ocean population from analysis of catch.

These techniques are either being applied or are being developed for application to the Sacramento River. Some modifications to existing systems might be very beneficial.

Under the constraints of the current operation of RBDD, some improvements could be made by using 24-hour stop-motion video on all three fish ladders. This would remove the night correction factor since all fish would be enumerated. Furthermore, digital image analysis should be able to distinguish chinook from other fish and might be able to distinguish between runs based on the color of the fish.

Ideally, RBDD would be redesigned to be more fish-friendly. Enlarging the fish ladders has been proposed, and would improve upstream passage conditions. If the gates could be modified to be top flow instead of bottom flow, downstream passage could also be improved. This might induce the salmon to attempt the probably impossible 3-meter jump over the dam.

Even if the dam was modified such that it could be run year-round, high winter flows would sometimes require the gates to be raised, and an unknown amount of winter run would pass without being counted. CDFG and USFWS are continuing ladder counts and attempting to update the video analysis system.

Mark-recapture studies offer a lot of potential, although when populations are low, it is difficult to get enough carcasses to tag. This could be alleviated by adding external carcasses. The large size of the river makes for low carcass recovery rates, which might be partially augmented by diving in deep holes where carcasses might accumulate. CDFG and USFWS have programs in place that would make this possible. The run timing information generated by these studies should be used to expand RBDD counts.

If aerial surveys continue, a replacement for Frank Fisher should be trained by Frank so that continuity is maintained. Visual surveys are observer dependent, and this dependency must be addressed if the surveys are used as an escapement index.

The extensive and intensive juvenile chinook sampling programs in the Sacramento should be integrated. Efforts should be directed towards an estimate of juvenile production rather than migration timing. This could be accomplished within the IEP.

Finally, the recent development of sensitive probes that detect alleles specific to winter chinook should be applied. Port sampling is already conducted to obtain heads of coded-wire-tagged salmon, and could be expanded to randomly sample total catch. Only very small amounts of material are needed for the analysis. The data generated would be extremely valuable, providing information on ocean distribution and fishing mortality as well as an abundance estimate.

## 5 Time to Detect Increasing Population Trend

The goal of measuring winter-run escapement is to detect significant changes in the run size. Because the environment affects salmon reproduction and survival, we expect run sizes to change from year to year. For instance, during the dramatic exponential decline of the winter run between 1967 and today, the population actually increased some years. We can only see the real decline when we look at several years of data. Prior to 1986, the deviations of the population from the exponential decline is due solely to environmental variability; almost all fish were counted so sampling error was very small. Currently, sampling error is significant, and some of the year-to-year variation since 1986 is due to this error. We know intuitively that sampling error might pose a problem when we try to decide if the run size is increasing or decreasing. In this section, we determine the time required to detect a positive growth rate in the face of natural variability and sampling error.

## 5.1 Approach

The basic approach used was to generate artificial escapement time series and subject them to linear regression in order to determine how long time series would be needed to detect population increases given expected growth rate, some natural variance of growth rate, and sampling error. The natural variance of growth rate was calculated from the escapement of three-year-old winter-run chinook during the period of 1967–1995. During this time, escapement declined at an average rate of 0.198 $\text{year}^{-1}$, with a variance of 0.257 $\text{year}^{-2}$.

Artificial escapement time series were produced by starting with observed escapement in 1993, 1994, and 1995 and applying an exponential growth equation:

$$N_t = N_{t-3}e^{\mu_t} \qquad (1)$$

where $N_t$ = number of salmon returning to river at time $t$, $N_{t-3}$ = number of salmon that spawned the current population, and $\mu_t$=actual instantaneous growth rate.

The growth rate, $\mu_t$, was calculated by adding an error term to the "expected" growth rate. The error term was calculated by sampling randomly from a normal distribution with a mean of 0 and variance of 0.257. One hundered data sets were generated per trial.

To take into consideration the effects of counting only some of the spawners, time series were constructed as above and then sampled by applying a binomial distribution. This is probably optimistic since overestimates at RBDD are probably larger than underestimates, i.e., the distribution of errors is not normal but skewed.

The log of the escapement time series was taken, and a subset of the data was taken for regression analysis according to the length of time. The probability of being able to detect a population increase is estimated from the fraction of $P$ values below 0.05. This analysis was repeated for combinations of expected growth rates, sampling periods, and sampling errors.

## 5.2 Results

If we could measure the entire run with perfect accuracy and precision, and it was recovery at a true rate of 0.20 per year, it would take about 12 or 13 years on average before we could conclude the population was increasing (Fig. 1). Even at much higher growth rates, it takes six years of returns. This should not be too surprising, since there is substantial environmental variability and it takes three years for winter chinook to complete their life cycle. If we count only 15% of the fish, detecting population increase with a growth rate of 0.2 per year takes about 22 years on average (Fig. 2). In summary, unless population growth rates are substantially larger than the rate at which winter chinook declined, we cannot expect to detect the effects of restoration measures for at least ten years.

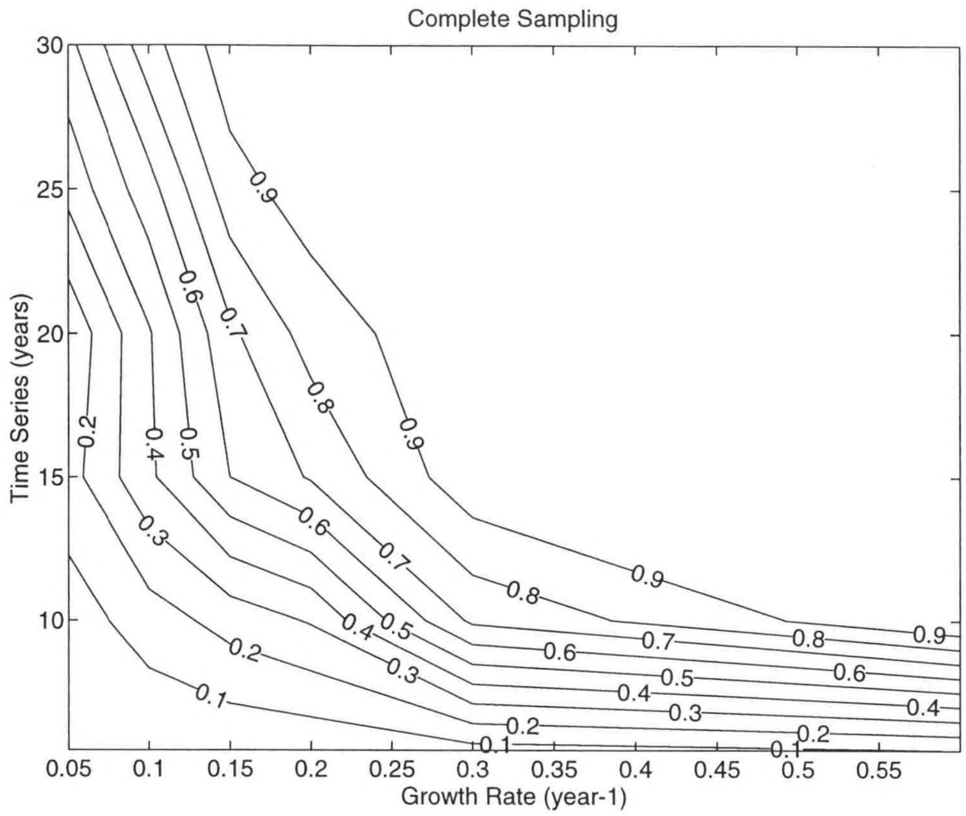


Figure 1: The probability of detecting a population increase using linear regression as a function of average population growth length and observation period, with complete sampling of run.

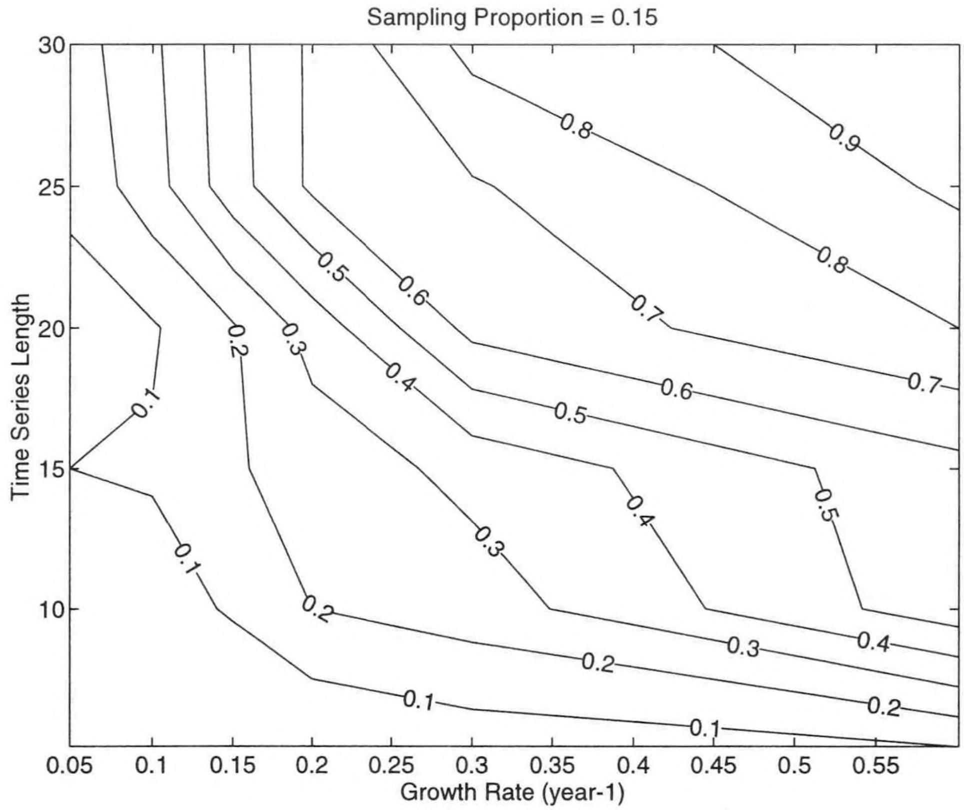


Figure 2: The probability of detecting a population increase using linear regression as a function of average population growth length and observation period, when sampling 15% of run.

## 6 Citations


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