A CONTROL SYSTEM FOR INTRASEASON SALMON MANAGEMENT

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Management of Salmon populations in large rivers like the Skeena (B.C.) is usually done in two stages. First long range goals and data are used to set annual target exploitation rates for each stock or population that spawns in the river.[1] Second, actions are taken within each fishing season to regulate catches so as to produce the target exploitation. The most difficult monitoring and decision problems are associated with intra-season management; the purpose of this paper is to outline a control system for dealing with these problems.

At the beginning of each fishing season, the salmon manager has only crude estimates of the expected runs (A "run" of any species is the number of fish attempting to enter the river; catch is removed from the run, leaving escapement = run - catch). He also has estimates of the proportion of the run that will enter the river during each week of the season. As the season progresses he must monitor catches and escapements so as to improve his estimates of the total runs, and set harvest regulations accordingly. Current management practice involves week by week regulation of exploitation rates (proportion of run actually caught) by changing the number of days open. At the end of each week, the number of open days for the next week is announced. Historical data is used to estimate the relationship between exploitation rate and days fished, but this relationship is by no means perfect since the number of fishing boats is poorly controlled.

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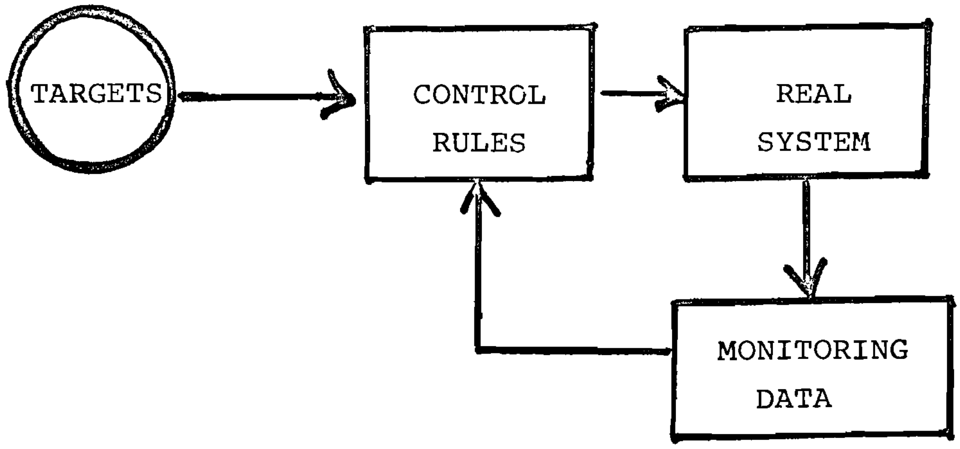
[1] Walters, 1974. "Optimal Harvest Strategies..." IIASA Working Paper 74-4

The fishermen, unfortunately, have only limited ability to discriminate among the various species that may be entering the river during any week. Each stock has a different optimum exploitation rate, and may suffer genetic damage in the long run if some segments of it (e.g., early running fish) receive different exploitation rates than others. Essentially the weekly exploitation rate is a blanket measure that must be applied across all stocks which are present at that time.

THE GENERAL CONTROL FRAMEWORK

The basic idea of a control system is very simple:



Given a real system that cannot be fully observed (the fishery), monitoring data is used,along with targets (goals), to decide on controls (regulations). The aim of control system design is to produce a good set of "control rules" for translating accumulated data into management actions or controls.

Figure 1 diagrams the functional elements for an intra-season salmon control system. The basic control variable is the number of "open days" for fishing each week; the elements of the diagram show the various calculations (functional relationships) and intermediate estimators which should be used in arriving at a control value for each week.

The flow of information is as follows:

(1) a preseason forecasting model is used to generate initial estimates of the runs to come

(2) before the beginning of each week, cumulative catch and escapement data are used to generate: a) a prediction of fishing effort (boat-days) for the week, and b) a new estimate of the total run size

(3) the new estimate of total run size is combined with the preseason forecast to give a revised overall forecast of the total run

(4) the revised overall forecast and cumulative catch to date are compared to the overall target rate in order to decide a target rate for the week

(5) the number of open days to allow is calculated as a function of the target rate for the week, the predicted effort, and the expected catchability coefficient (proportion of stock taken by one unit of effort).

Steps (2)-(5) are repeated each week; thus the control system proposed in Figure 1 results in changing regulations as new information is obtained.

ELEMENTS OF THE CONTROL SYSTEM

This section develops the conceptual components of Figure 1 in more detail and provides an empirical basis for implementing the system in practice. Extensive use is made of unpublished data kindly provided by F.E.A. Wood and Ed Zyblut of Environment Canada.

Control Component 1: Preseason Run Forecasts

Many kinds of data and models could be used for run forecasting, and the various alternatives should be carefully compared in terms of costs relative to statistical accuracy. Figure 2 shows one possibility for the Skeena sockeye, based on river flow data and downstream smolt counts. This forecasting model and several alternatives are described more fully elsewhere[2]; essentially they are non-linear regression formulae based on the Ricker stock-recruitment model. All methods take the age distribution of returning adults into account, and both could be made at least two years before they are actually needed for management. The various methods give similar expected forecasting errors:

Method	Variance of Forecasts
escapement-flow (no smolt counts)	3.02×10^{11}
smolt counts-flow	2.24×10^{11}

(A variance of 2.24 X 10" means a standard deviation of 469,000; about 67% of the forecasts should be within 469,000 of the actual runs)

Staley[2] has developed similar forecasting models for pink salmon (Figure 3). The best of these models has a variance of 0.46×10^{12}, using escapements and river flows as regression inputs.

Whatever the preseason forecasting system that is considered best, its key characteristic for this analysis is its forecasting variance. The variance is used to weight

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[2] Staley, M. Run forecasting for sockeye and pink salmon of the Skeena River. IIASA working paper.

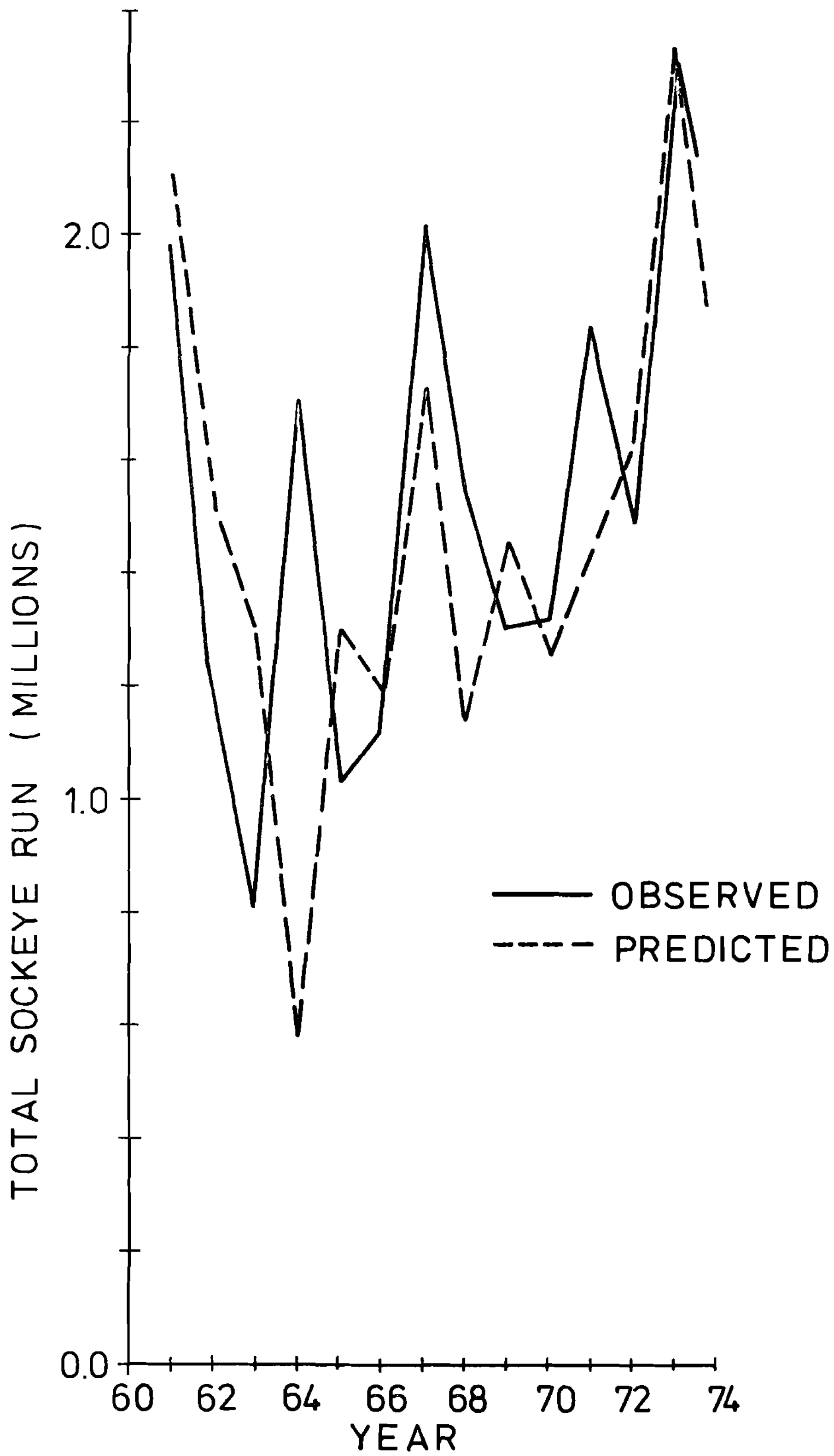

FIGURE 2. Preseason sockeye forecasts using smolt counts and stream flow. From M.L. Staley (in preparation).

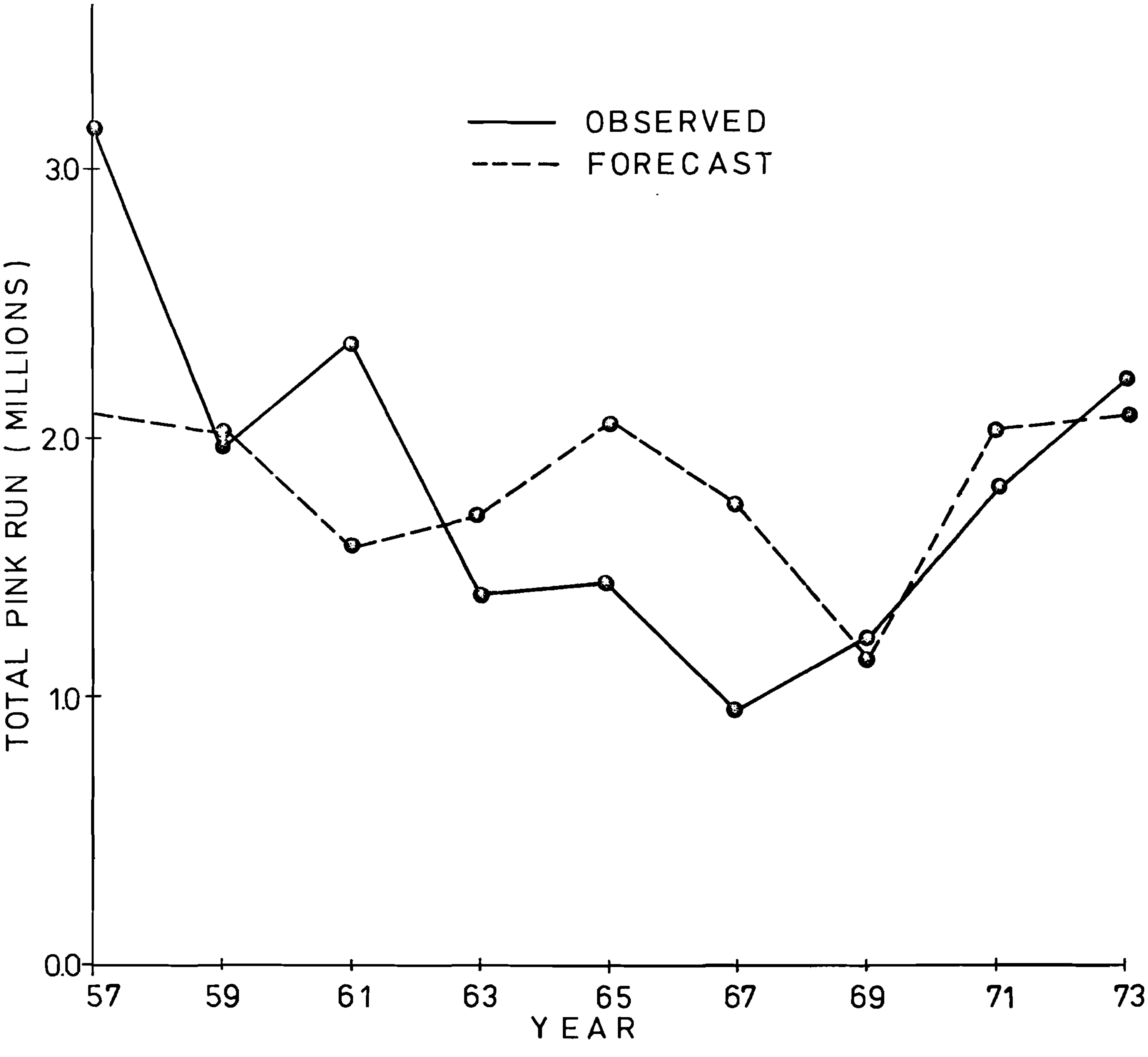

FIGURE 3. Preseason forecasts for odd year pink salmon, using a Ricker model and stream flow data from M.L. Staley (in preparation).

preseason versus within-season run estimates to arrive at a (changing) best overall prediction for the run.

Control Component 2 : Within-Season Run Estimates

Cumulative run timing curves for the Skeena are presented in Figure 4. It is apparent that there is considerable variation from year to year in the proportion of fish that have entered the fishery by any date; we can find no simple way to predict whether a given year will be "early", average, or"late". Figure 4 also presents variance estimates for the cumulative proportion of fish returned, by date (these variance estimates were calculated directly for each date by taking sums of squares deviations of the observed proportions for the date from the mean observed proportion); these variance estimates are essential in developing a method for weighting within-season versus preseason run estimates.

Given the cumulative catch plus escapement up to any date, and the mean cumulative proportion expected to have returned by that date (Figure 4), the within-season total run estimate is simply

$$\text{total run estimate} = \frac{\text{(Catch + Escapement to date)}}{\text{(Cumulative Proportion to date)}} \qquad (1)$$

Dr. J. Bigelow of IIASA has kindly developed an approximate (second order) variance estimator for this run estimate; it is

$$\sigma^2_{w_t} = \frac{R_t^2 \sigma^2_{P_t}}{P_t^4} \left[1 + 2 \frac{\sigma^2_{P_t}}{P_t^2}\right] \qquad (2)$$

where

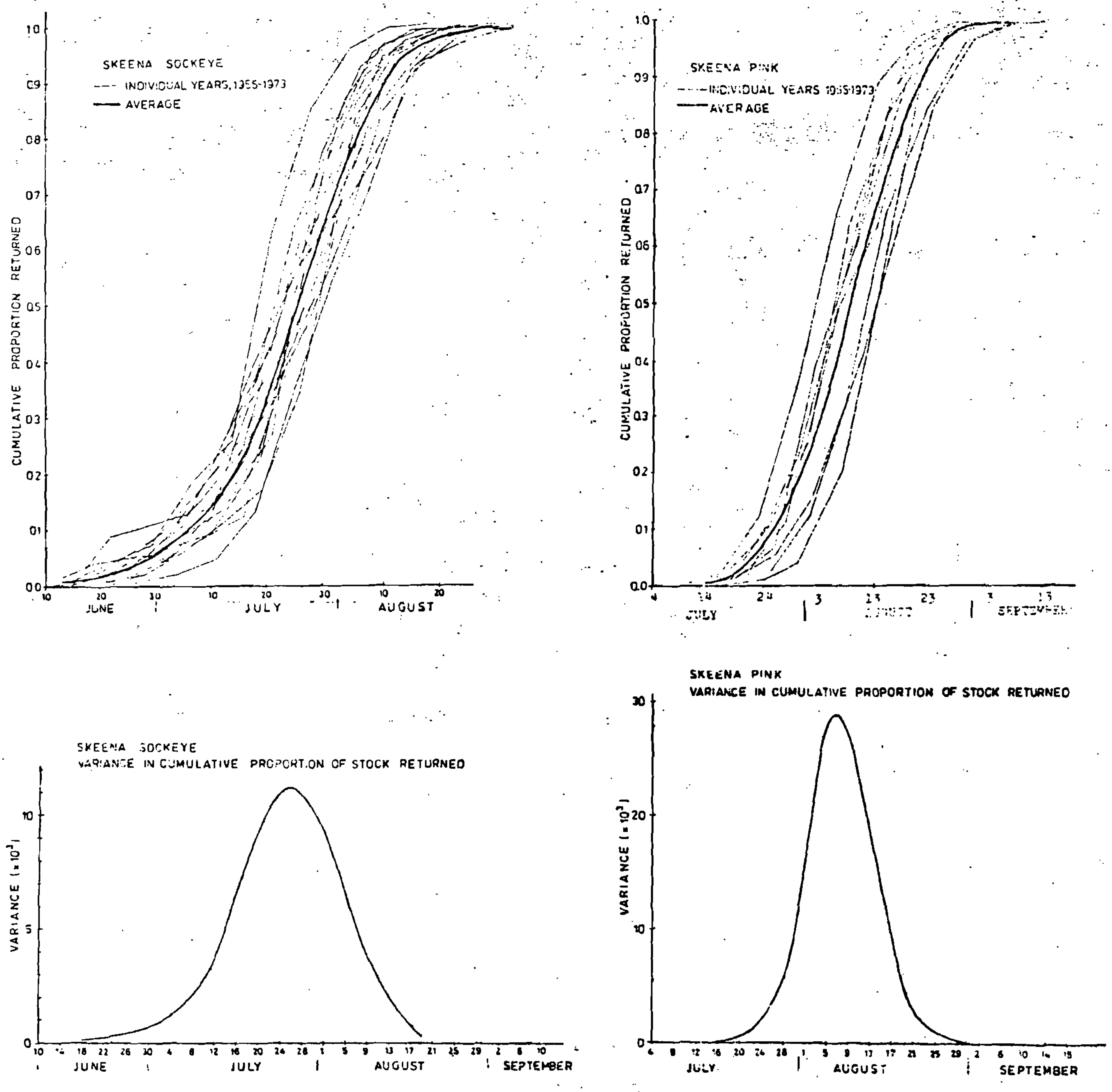

FIGURE 4. Cumulative return curves for Skeena River sockeye and pink salmon, and estimates of year to year variance in the cumulative proportion.

$\sigma^2_{W_t}$ = variance of the total run estimate for time t in the season

$\sigma^2_{P_t}$ = variance of the cumulative proportion returned (Figure 4)

P_t = mean cumulative proportion returned at time t (Figure 4)

R_t = cumulative catch plus escapement up to time t.

Note that the variance estimate $\sigma^2_{W_t}$ consists of a "weighting factor" which can be computed from data in Figure 4, multiplied times the square of cumulative catch plus escapement. Weighting factor curves for the Skeena are presented in Figure 5; the variance estimate for the within-season run estimate at any date is simply the Figure 5 weighting factor times (catch + escapement to date)^2. It is apparent from Figure 5 that the within-season total run estimates are quite unreliable until over half of the run is past.

There is, of course, a fly in the ointment: cumulative catch plus escapement is never known exactly as of any date; cumulative escapement is measured at the spawning grounds, with a time delay of at least one week. An escapement estimate for each week is available from test fishing, and the variance of this estimate should be incorporated into equation(2) for future analyses.

Control Component 3: Weighted Overall Run Estimates

The next step is to find a way of weighting the preseason and within-season run estimates (previous two sub-sections) to give the best overall run estimate for each date. Suppose we consider writing this overall estimate as a weighted average of

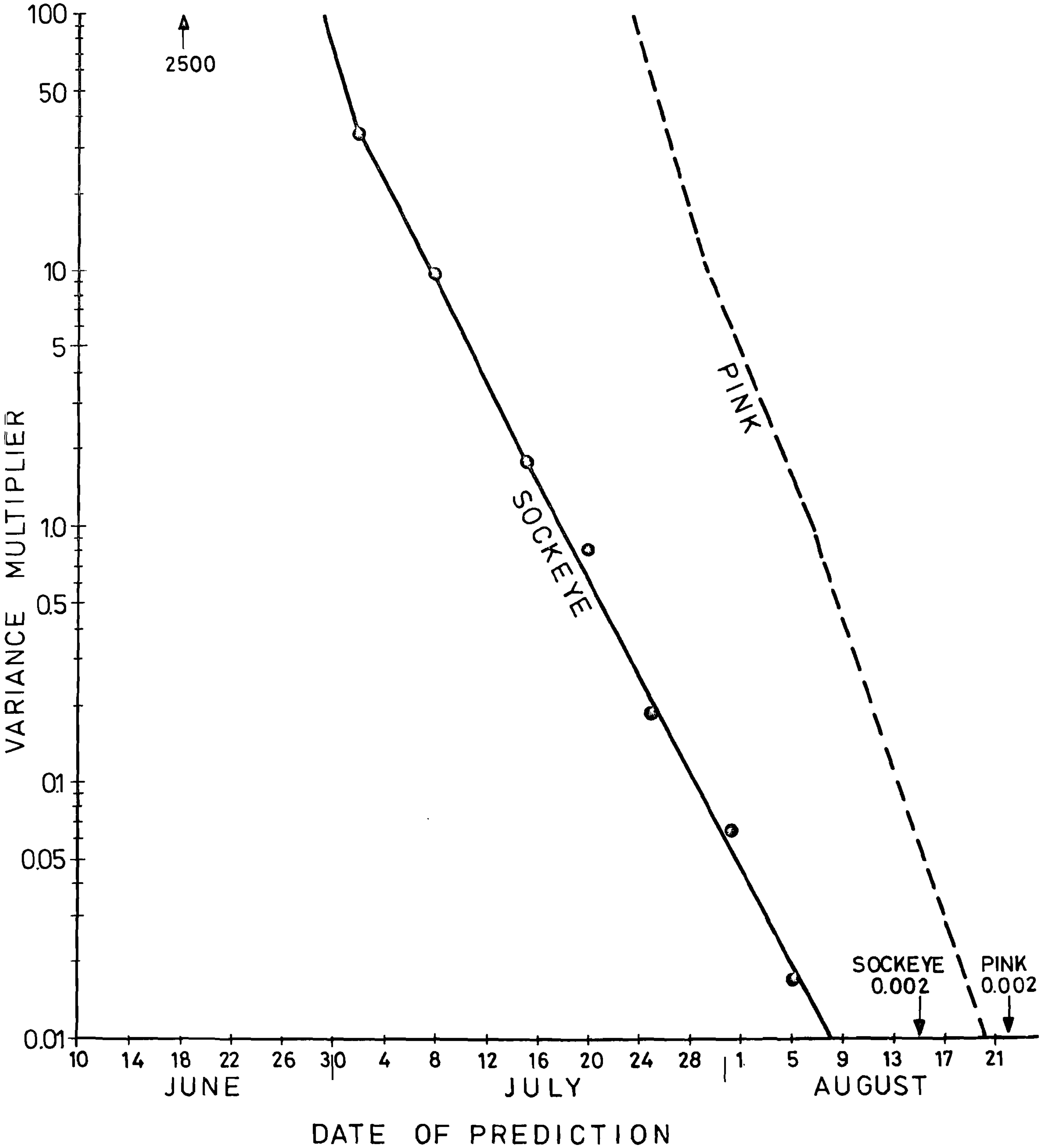

FIGURE 5. Weighting factors for computing variances of within-season total run estimates. Explanation in text.

the two estimators:

$$\hat{\hat{R}} \equiv \begin{pmatrix}\text{overall run} \\ \text{estimate based} \\ \text{on data to time} \\ t\end{pmatrix} = W_t \begin{pmatrix}\text{Preseason} \\ \text{estimate}\end{pmatrix} + (1-W_t) \begin{pmatrix}\text{within} \\ \text{season} \\ \text{estimate}\end{pmatrix} \quad (3)$$

where W_t is the weighting factor ($0 \leq W_t \leq 1$). The variance of the overall run estimate is then

$$\sigma^2_{\hat{\hat{R}}_t} = W_t^2 \ \sigma_f^2 + (1-W_t)^2 \sigma^2_{w_t} \quad (4)$$

where σ_f^2 = variance of preseason forecast (see component 1 subsection above)

$\sigma^2_{w_t}$ = variance of within season forecast (see component 2 subsection above)

This formula suggests a way of choosing the W_t, namely so as to minimize $\sigma^2_{\hat{\hat{R}}_t}$. If we differentiate equation (4) with respect to W_t and solve for the minimum, we get

$$W_t = \frac{\sigma^2_{w_t}}{\sigma_f^2 + \sigma^2_{w_t}} \quad (5)$$

This equation implies that W_t should be near 1.0 early in the season (when $\sigma^2_{w_t}$ is very large), and decrease progressively as $\sigma^2_{w_t}$ decreases.

Sample weighting curves using equation (5) and variance estimates from the previous subsections are presented in Figure 6. Since $\sigma^2_{w_t}$ depends on catch plus escapement, no single weighting curve can be drawn and used under all conditions. The sample curves were developed using average catches plus escapements, and they should be adequate for most practical situations. To illustrate the use of Figure 6 in conjunction with equation (3), let us suppose that it is July 5, that we

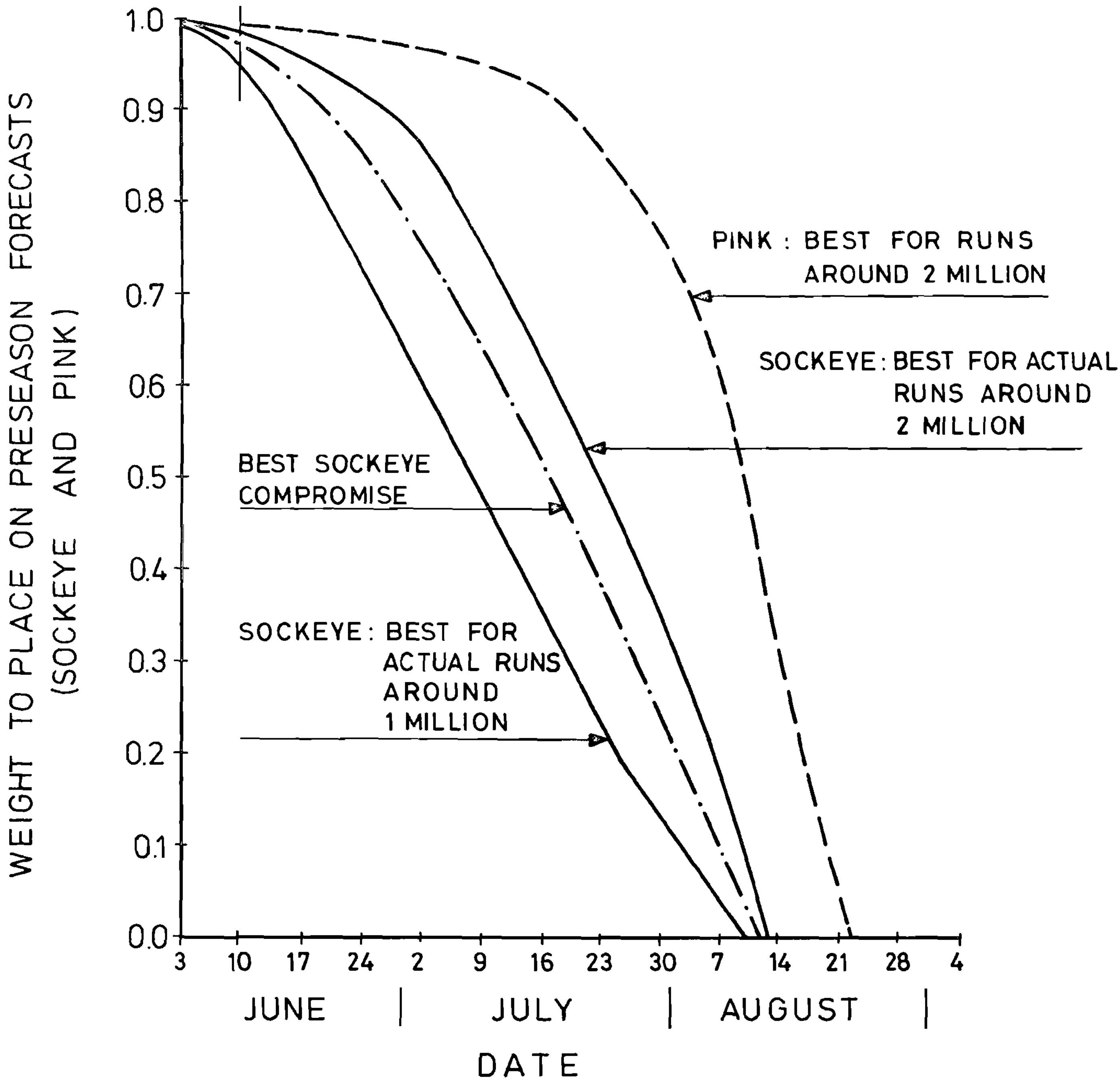

FIGURE 6. Weighting factors for preseason versus within-season total run estimates. Explanation in text.

have a preseason sockeye forecast of 1.8 million, and that the catch plus escapement to date has been 0.15 million. From Figure 6 the approximate weighting factor for July 5 is 0.7. Using Figure 4, we estimate that 10% of the fish have already passed, so the within-season run estimate is 0.15 million/0.1 = 1.5 million. The best overall run estimate as of July 5 is then

$$R_{\text{July }5} = (0.7)(1.8 \text{ million}) + (0.3)(1.5 \text{ million}) = $$
$$= 1.71 \text{ million sockeye}$$

<u>Control Component 4: Weekly Target Exploitation Rate</u>

It would be easy to establish a target exploitation rate for each week if there were only one stock; we would simply take

$$\text{target rate} = \frac{(\text{total desired catch}) - (\text{catch to date})}{(\text{total remaining run})}$$

Using this target calculation would result in the same rate every week if a) run timing were exactly average, b) the run forecast were perfect, and c) effort were perfectly controllable. Otherwise, the calculation is simply saying that the rate should be kept as steady as possible relative to the best estimate of the remaining run to come.

The analysis becomes much more difficult for overlapping sockeye and pink runs. The overall (total season) target rates for the two species will almost always be different. There are three management possibilities:

(1) try to design special gear regulations to allow more selective exploitation

(2) try to design a complex target curve for weekly exploitation rates, considering relative run sizes

at different times[3].

(3) simply switch from managing one species to managing the other at some fixed time (for example when the pink catch becomes the largest).

An example of a complex target curve is shown in Figure 7; for known run size and perfect effort control, curves of this type would minimize the week-to-week variation in exploitation rate seen by each stock, subject to the constraints that the overall target rate for both species be met.[3] However, it is difficult to apply such curves consistently in the adaptive control context; to do so would require the manager to redo a fairly large dynamic programming optimization every week through the reason, which is hardly practical.

We favor the switching option, because it can be practically implemented and efficiently programmed for simulation tests. Let us assume that management will be switched from sockeye to pinks at time "T" within the season (most likely around July 30), and that the overall target exploitation rates are

E_s (Sockeye, e.g. 0.5)

and E_p (pink, e.g. 0.4).

These may be revised each week as the overall run estimates are revised. Let the cumulative proportions of fish that are expected to have arrived before any time "t" be

${}_sP_t$ (sockeye)

and ${}_pP_t$ (pink)

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[3] Walters (1974) "Regulation of escapement for overlapping runs of sockeye and pink salmon" IIASA mimeo report.

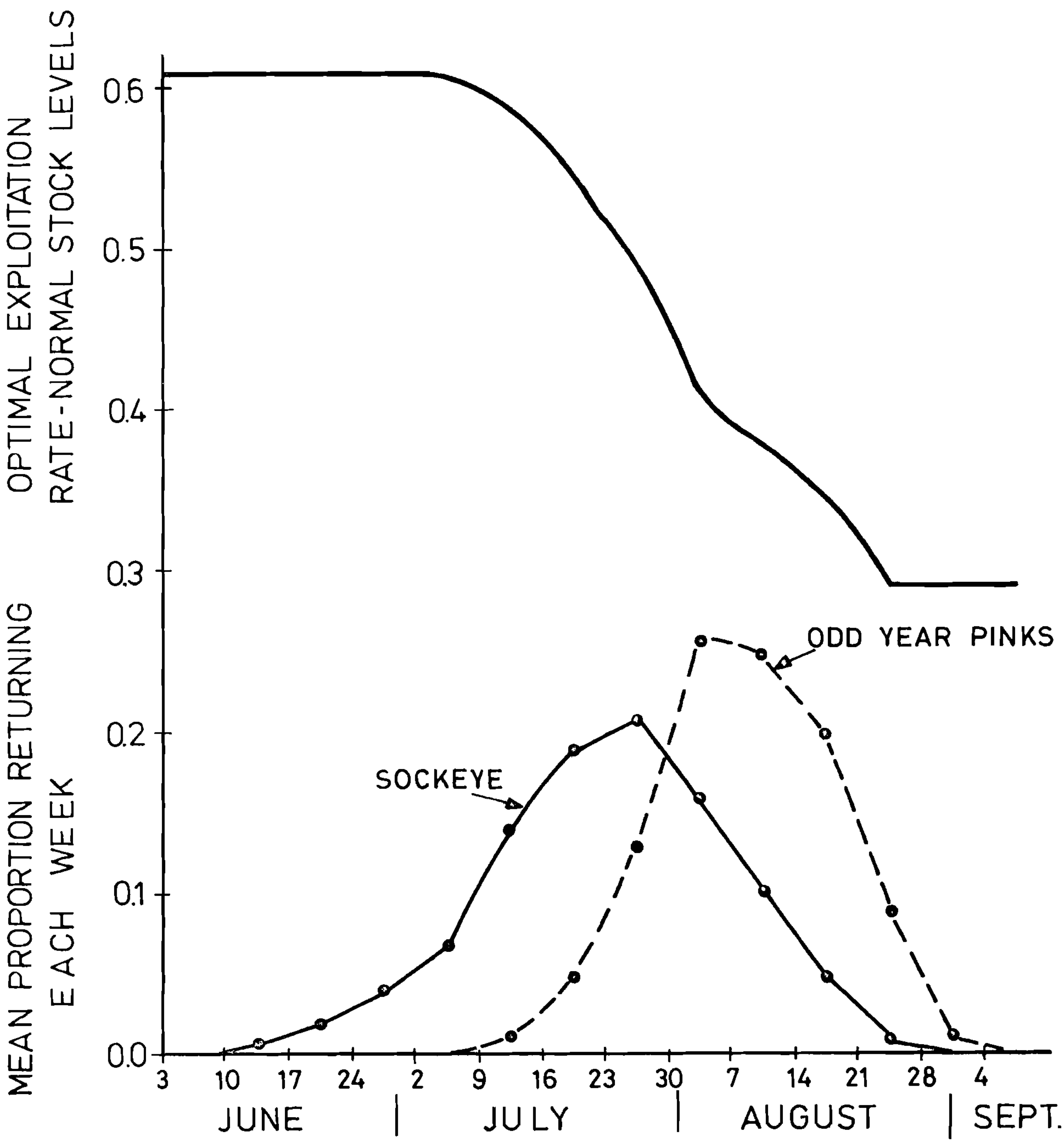

FIGURE 7. A complex target curve for weekly exploitation rates; this curve could be reasonably followed only if effort were completely controllable and total runs were known exactly. Practical application not recommended.

(These expected proportions are given in Figure 4). Thus $_sP_T$ is the proportion of sockeye that should have arrived by the switch time ($_sP_T$ = 0.68 for July 30 switch). Let the cumulative catches up to time t be

$$_sC_t \qquad \text{(sockeye)}$$

and

$$_pC_t \qquad \text{(pink)}$$

Let the best total run estimates as of time t be (component 3 above)

$$_s\hat{\hat{R}}_t \qquad \text{(sockeye)}$$

and

$$_p\hat{\hat{R}}_t \qquad \text{(pink)}$$

(Note that these run estimates are based partly on preseason forecasts and partly on catch plus escapement up to time t).

By analogy with the single stock case, we argue that the exploitation rate for weeks prior to T (the "sockeye weeks") should be set as

$$\begin{array}{l}\text{target rate} \\ \text{(weeks } t < T)\end{array} = \frac{E_s\, {_s\hat{\hat{R}}_t} - {_sC_t} - (1-{_sP_T})E_p\hat{R}_s}{({_sP_T} - {_sP_t})\hat{\hat{R}}_s}$$

This equation is actually simple: the numerator is (total desired sockeye catch) less (sockeye catch to date) less (sockeye catch expected during the "pink weeks" after time T; the denominator is the expected total run over the remainder of the sockeye weeks. The equation can give negative rates if sC_T is already too large; in this case the exploitation rate should be zero.

For weeks T and after (the "pink weeks"), the analogous equation is

$$\begin{array}{c}\text{target rate}\\ (\text{weeks } t \geq T)\end{array} = \frac{E_p \; {}_p\hat{\hat{R}}_t - {}_pC_t}{(1 - {}_pP_t)\; \hat{\hat{R}}_p}$$

This equation is simply the additional desired pink catch divided by the additional expected pink run. It may give negative rates, especially if the pink catch during the wockeye weeks has been high; in such cases the optimal rate is obviously zero.

The switching policy outlined above should lead to difficulties only in the extreme years when no catch of one or the other species is desired. Our long range production analyses indicate that such situations should occur less than once per decade, especially if variance minimizing harvest strategies are used. We will examine the consequences of these infrequent policy failures in a later section.

Control Component 5: Within-Season Effort Forecasting

Figure 8 shows that weekly effort levels can be predicted from catch per effort the previous week. Apparently the fishermen base their decisions at least in part on how well the fishing has been. However, catches in previous years seem to also play some role; the run in 1972 was late, but fishing effort started to increase as usual (high points for 1972 in Figure 8). The simplest assumption is that the fishermen use a weighted prediction of catch per effort:

$$\begin{matrix}\text{expected} \\ \text{catch/effort}\end{matrix} = D_t \begin{pmatrix}\text{catch/effort} \\ \text{last year for} \\ \text{week } t\end{pmatrix} + (1-D_t) \begin{pmatrix}\text{catch/effort} \\ \text{week } t\text{-1 this} \\ \text{year}\end{pmatrix}$$

where D_t is a weighting factor $(0 \le D_t \le 1)$ that appears to change as shown in Figure 9. This expected catch per effort can be used as the point along the X axis of Figure 8, and effort predicted from the trend curve.

There has been significant license reduction since 1971, and this is reflected as decreasing asymptotes of the curves in Figure 8. It appears that we can nicely simulate alternative licensing policies simply by changing the asymptote, though higher asymptotes appear to be associated with increased willingness to fish when the expected catch rate is low (apparently a natural human reaction to competition). Open entry investment and disinvestment processes could also be simulated by changing the asymptote according to simple dynamic rules (e.g., increase the asympote when last year's

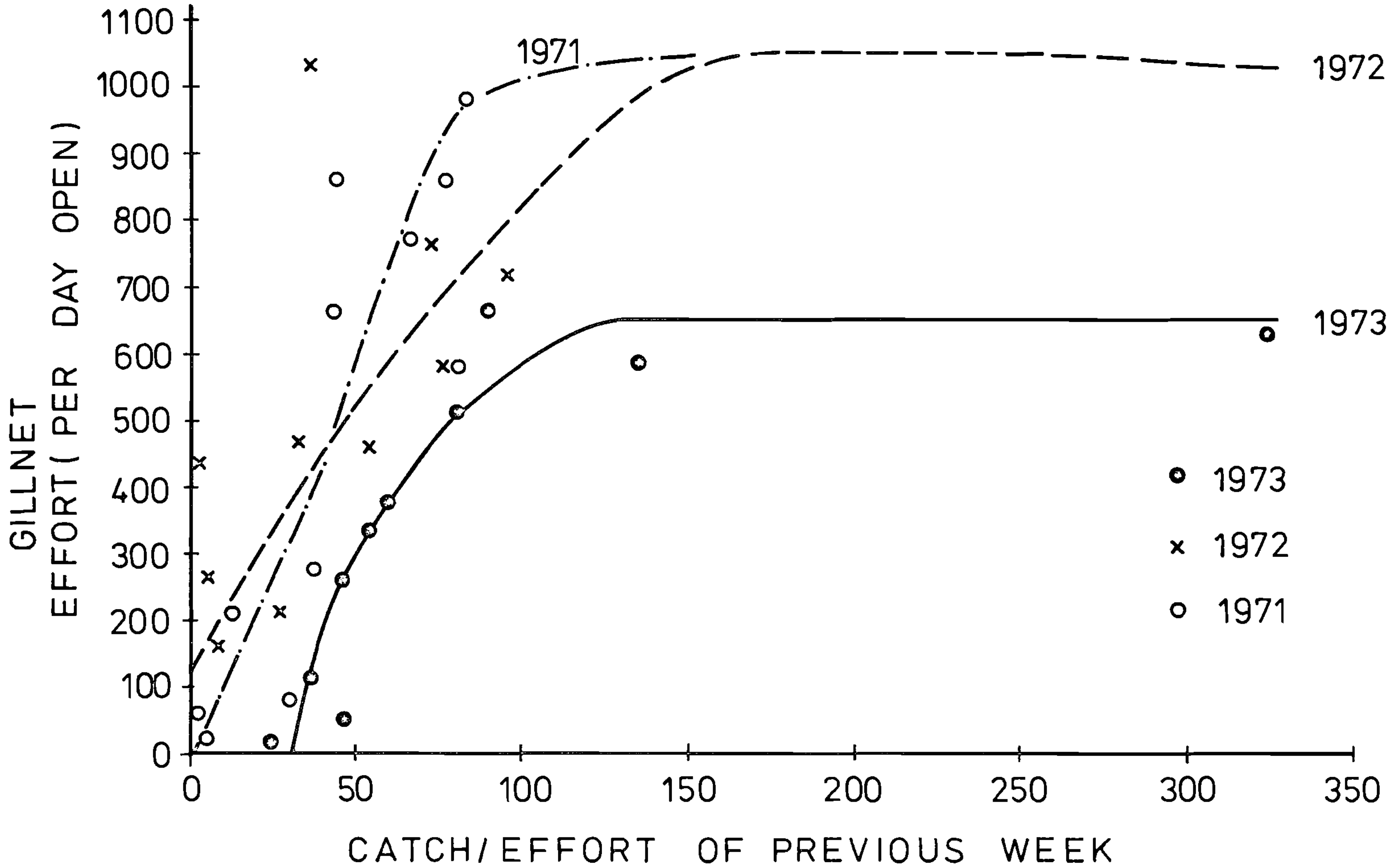

FIGURE 8. Prediction curves for weekly fishing effort as a function of last week's catch per effort. Note that asymptote depends on licensing policy.

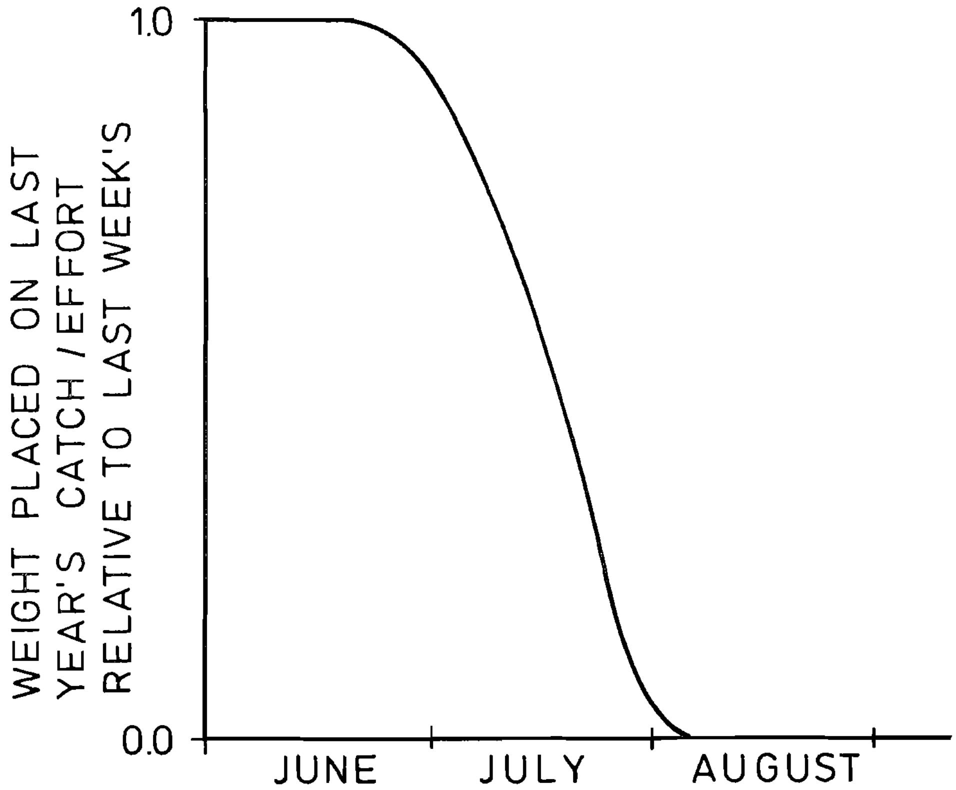

FIGURE 9. Weighting curve that fishermen appear to use in deciding whether to fish each week. Explanation in text.

returns were good, and decrease it after several years of poor returns).

The effort functional response (Figure 8) places severe constraints on management attempts to even out the exploitation rates across each fishing season. It appears that it will usually be necessary to overexploit the later segments of each run, since the fishermen are likely to miss the early segments. If the government encourages the fishermen to go out earlier, then the prediction curve will of course have to be modified.

Control Component 6: The Open Days Calculation

The components outlined above result in a target exploitation rate and a predicted effort level for each week. The final control step is to calculate the number of open days that should be allowed. Figure 10 shows the observed relationship for 1971 -73 between exploitation rate and total gill net effort (fishing days per open day times number of open days). This relationship is not good; apparently the same effort levels result in higher exploitation rates when stock sizes are low (early and late in the season). The average relationship can be described by a "catch curve".

$$U = (1 - e^{-c(Ed)}) \qquad (6)$$

where

U = realized exploitation rate

c = catchability coefficient

E = effort per day open

d = days open

From Figure 10, $c \approx 0.0008$, but this coefficient is likely to change in response to technological innovation (e.g., better gill nets and more purse seine conversion).

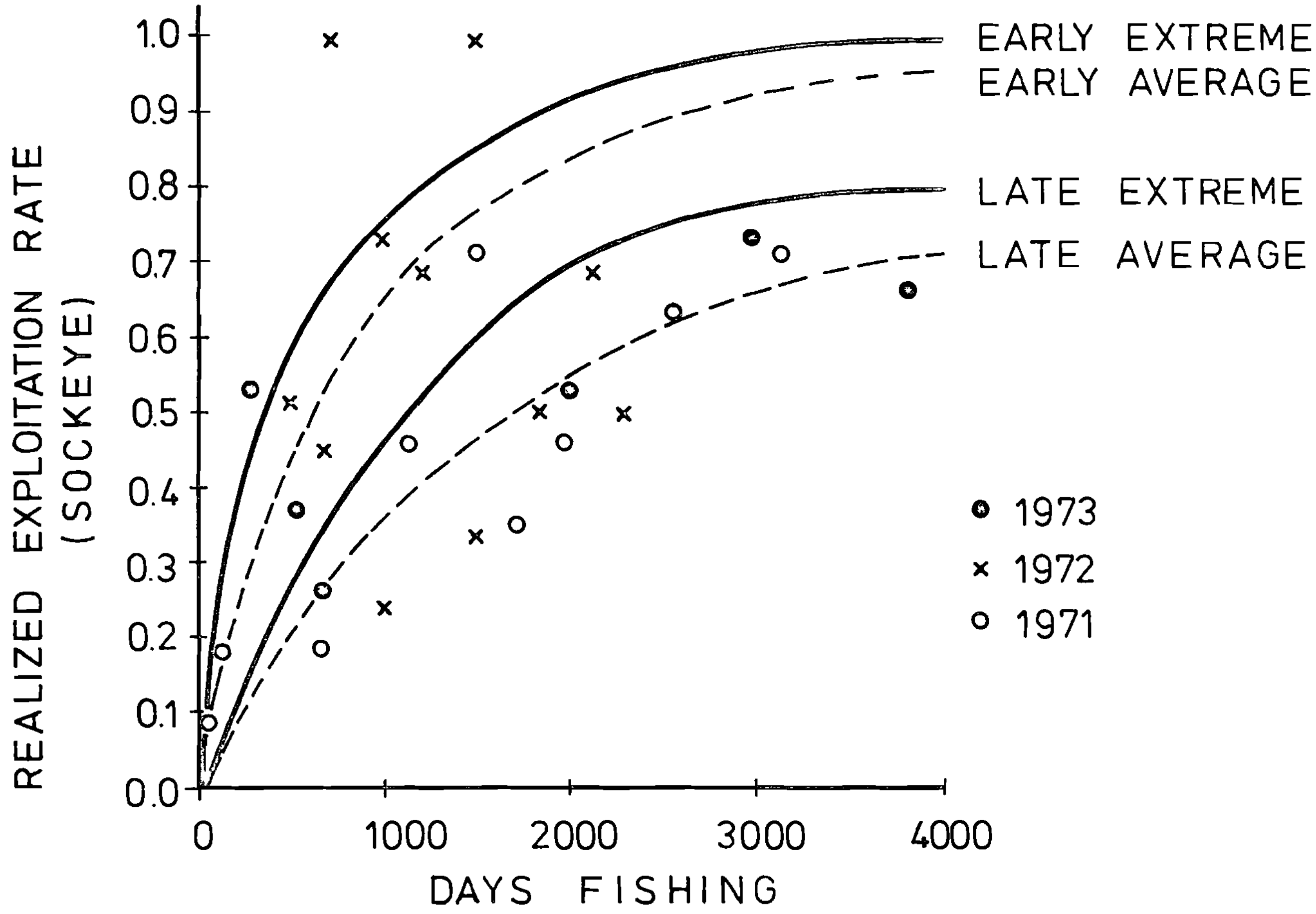

FIGURE 10. Observed relationship (1971-1973) between gill net effort and weekly exploitation rate.

For a crude estimate of open days to allow, we can substitute the target exploitation rate for U and the prediction effort (component 6) for E in equation 6, and solve for d. This gives:

$$\text{days open} = \frac{\left(\ln\left(1 - \text{desired expl. rate}\right)\right)}{-\,c\left(\frac{\text{predicted effort}}{\text{per day open}}\right)} \qquad (7)$$

This equation can of course predict that the number of open days should be very large, especially if the predicted effort is low; in that case it seems best to allow six open days. Also there should be no serious harm in rounding to the nearest half day.

Equation 7 might be improved considerably by making c variable over time in relation to expected stock size and rates of fish movement through the fishing area. Though we have considered only the gill net fishery, the procedure could be applied separately for the purse seine fishery. Also, it is obvious that estimates of c should be modified from year to year (and perhaps also within each season) using information on changing fishing power.

PERFORMANCE TESTS FOR THE PROPOSED SYSTEM

Clearly the control system proposed above should not be implemented unless it can be convincingly demonstrated to perform better than the existing, more intuitive system. The essential questions are: can the system meet overall target exploitation rates for most input situations, and does it result in a smooth sequence of exploitation rates across each season? By "input situation" we mean a combination of run forecasting errors, run timing patterns, and patterns of stochastic variation around the predicted effort and exploitation rate relationships (Figures 8 and 10).

Simulation testing procedure

Obviously there are an infinite number of possible input situations, but by simulation we can face the control system with long sequences of randomized inputs representing a reasonable sampling of the possibilities. If the random inputs are chosen with probability distributions estimated from actual historical variability, we should be able to generate reasonable probability distributions for control errors.

The simulation test procedure is very simple. For any simulated year, we provide the control system (equations of the previous section) with the following inputs:

(1) total sockeye and pink stock sizes, generated from escapements in previous simulation years using an appropriate stochastic model for the stock-recruitment relationship (e.g., Walters, footnote 1)

(2) preseason forecasts equal to the total stock sizes from (1) plus a random error term chosen from a distribution with variance appropriate to the forecasting system (e.g., normal with mean 0.0 and variance 2.24×10^{11} for sockeye)

(3) a run timing pattern for the year, chosen at random from a representative set of possible patterns (Figure 4)

(4) a series of random multipliers (with mean 1.0) to generate variability in effort levels and catchability coefficients from week to week, around their expected values as given in Figures 8 and 10.

(5) A control strategy curve giving desired overall exploitation rate as a function of total stock size, for each species (e.g. as in Walters, footnote 1).

We then go through these steps for a long series of years (e.g. 500); any serious control failures that are likely to happen in practice (due to some peculiar combination of inputs) should appear somewhere in the sequence. By including escapement ⟶ recruitment dynamics in the simulation, we should also be able to detect any serious long term trends that control errors may introduce.

Boundary conditions (fixed parameters) for any simulation sequence include the maximum effort per day open, the mean catchability coefficients, and the control strategy curve. By doing many simulation sequences with different boundary conditions, we should be able to measure how basic policy changes (e.g., gear changes, number of licenses) are likely to affect the "controllability" of the seasonal fishing system.

Results of Performance Tests

Figure 11 shows the results of three 500-year test simulations, using different maximum effort levels (licenses available) per day open. In each case the control system was trying to follow a simple strategy curve (solid lines in Figure 11) suggested by Walters (footnote 1). Each graph point represents the overall exploitation rate achieved for one simulation year.

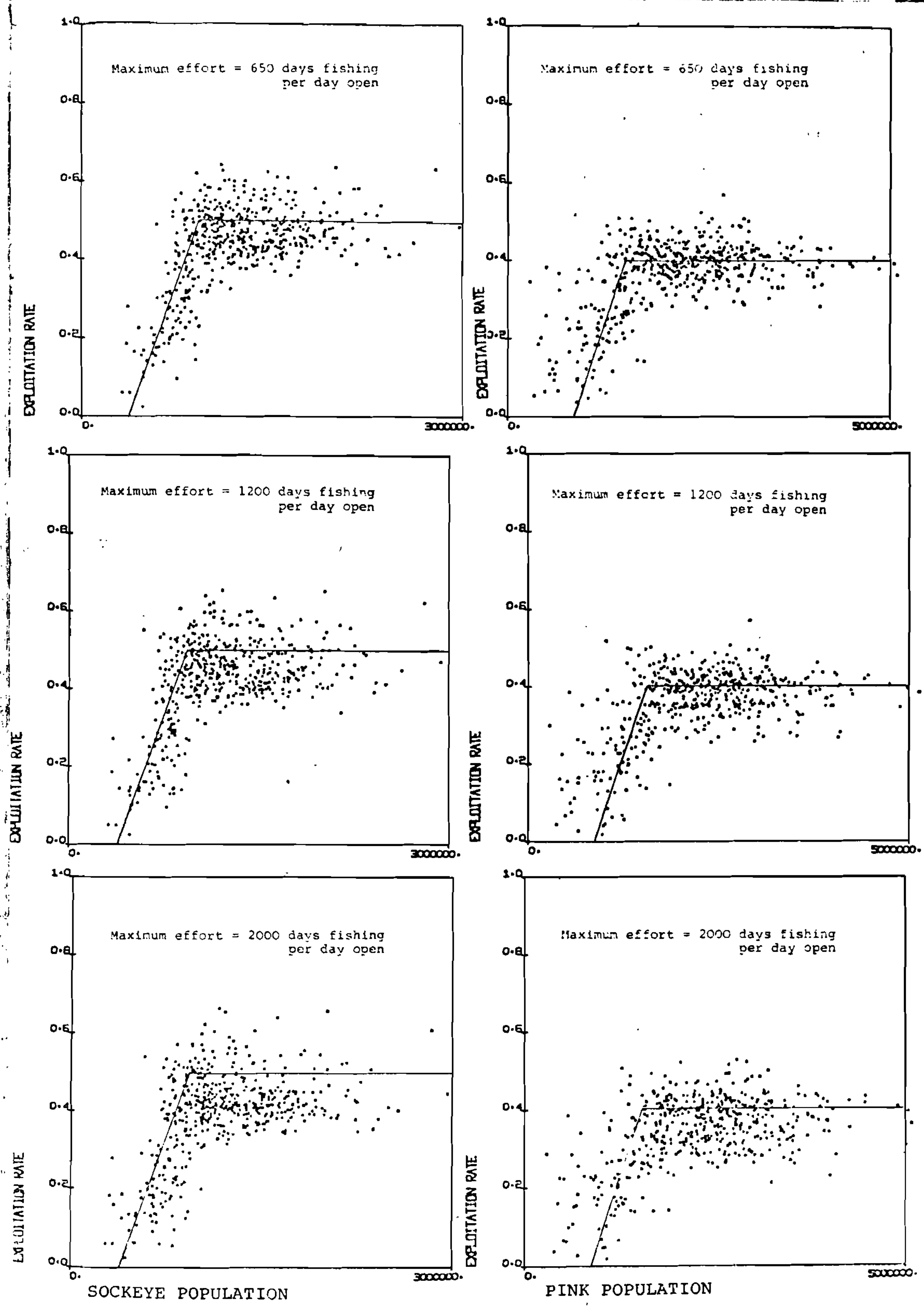

FIGURE 11 Simulation performance tests for the control system (explanation in text). Solid lines are target curves Panel A-600 licenses available; Panel B-1200 licenses available; Panel C-2000 lcenses available. (see footnote 4).

The control system obviously does not perform perfectly, especially for lower population sizes; low pink populations are almost always exploited at higher rates than desired. Better control is achieved at high population sizes: the simulated fishing effort in good seasons is more evenly distributed across weeks (the fishermen are willing to go out earlier), so there are more weekly opportunities to correct control errors. At low population sizes, the fishermen do not bother to go out except during the few peak weeks (mid-July - mid-August), so there are fewer opportunities to correct control errors. Figure 11 indicates that this problem would not be alleviated by increasing the number of licenses[4] available; the control system performs about as well when there are 2000 licenses (above 1970 level) as when there are 600 licenses (near the present level).

Figure 12 shows test simulations with strategy curves that should result in maximum average catch in the long run (essentially fixed escapement strategies, as currently used in practice). As measured by scatter around the target curves, control failure appears to be much more likely for these strategies than for the simplified strategy suggested by Walters (compare Figure 11). The maximum-yield strategies tend to produce lower average population sizes, which (as mentioned above) result in lower early-season effort and thus in fewer weekly opportunities to correct control errors.

As a final example, let us suppose that someone has devised a perfect method for preseason run forecasting. As shown in Figure 13, use of this method should result in surprising little improvement in control system performance. The other sources of uncertainty (run timing, realized effort,

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[4] by "license" in this context we mean a potential day fishing per day of open season. The actual number of licenses would be less.

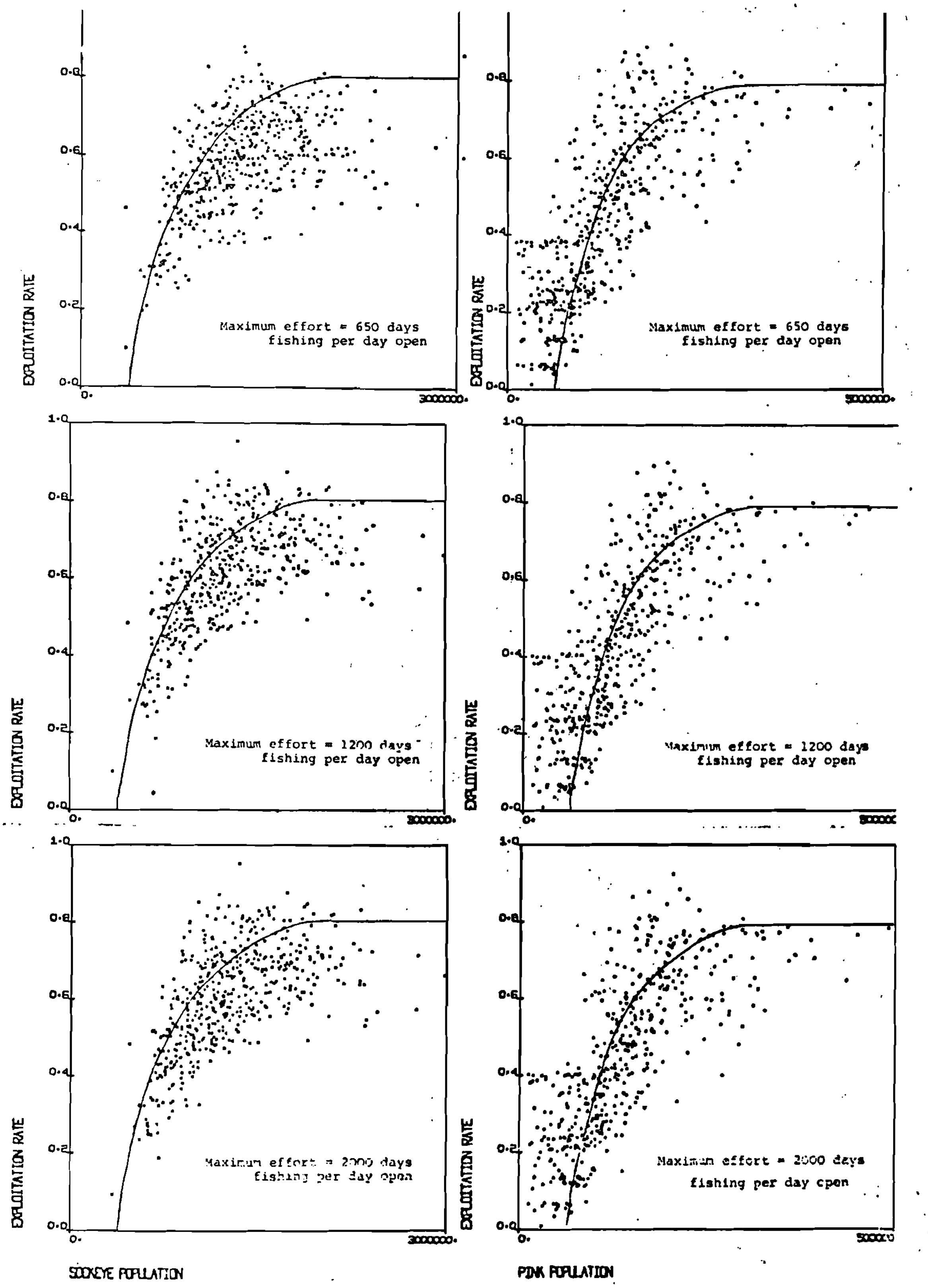

FIGURE 12 Simulation performance tests where the target curves are chosen to give long term maximum sustained yield. Panel A-600 licenses available; Panel B-1200 licenses available; Panel C-2000 licenses available (see footnote 4).

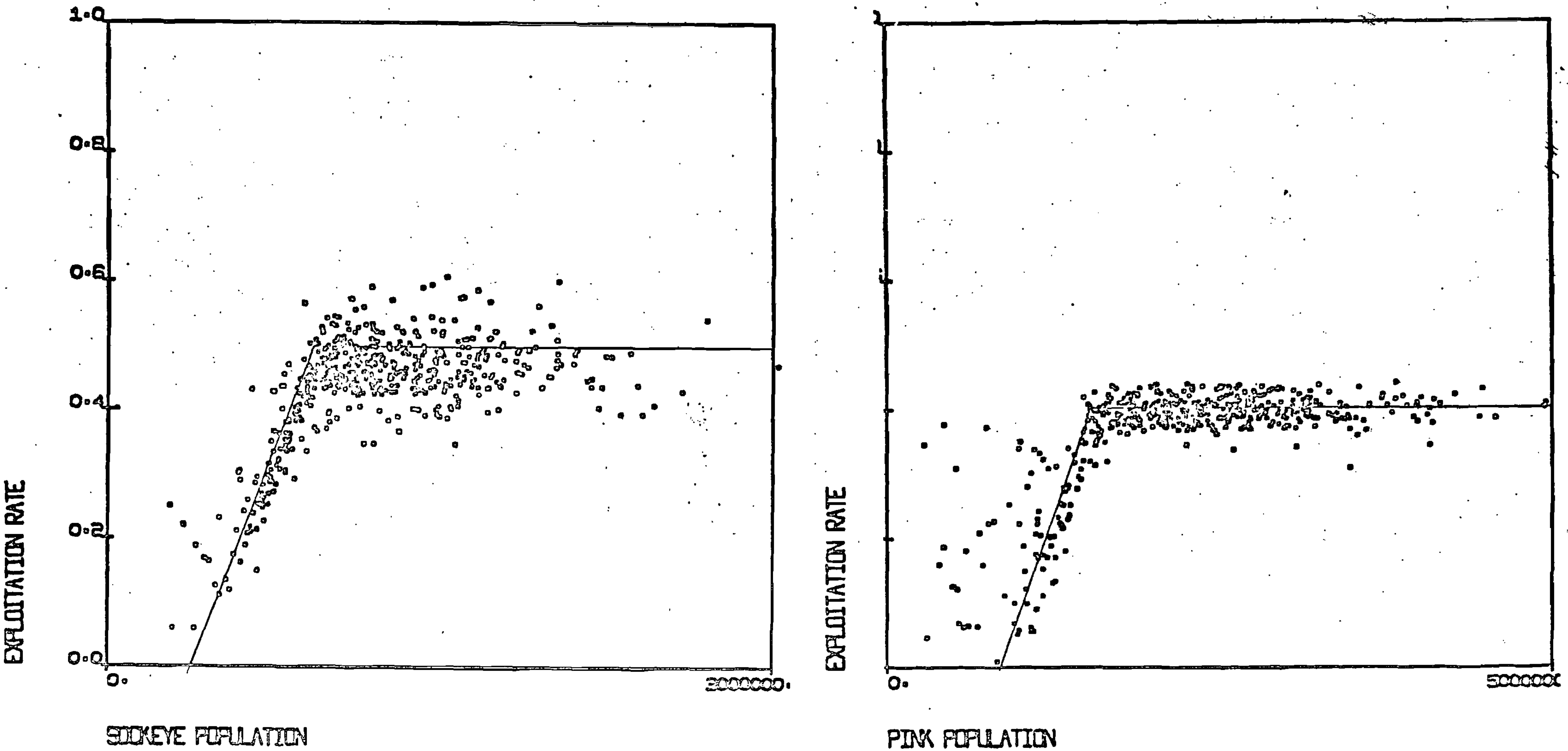

FIGURE 13 Control system performance assuming perfect preseason stock forecasts. Compare Figure 11

catchability coefficient) appear to be much more important than the preseason forecast. The implication of this observation for future research work is obvious: more emphasis should be placed on prediction of effort and catchability. In simple terms, it does little good to have better preseason run forecasts if most of the control problems are concentrated later in the season when run estimates are already fairly good due to within-season data.

It is difficult to compare the control error patterns in Figures 11-12 to actual management practice, since management control targets have apparently changed several times in recent years. Walters (footnote 1) presents management performance date (observed exploitation rates versus population size) for 1955-1974 on the Skeena River; this data shows about as much variability as Figures 11-12.

In terms of within-season stability of exploitation rates, the proposed control system does appear to be better than the intuitive system now used (figure 14). Current control policy results in erratic fluctuation of exploitation rates through each season; the control system should help to eliminate this fluctuation.

In summary, the major difficulties in within-season management appear to revolve around the unwillingness of fishermen to go out when catches are expected to be low. Opportunities for management control are largely limited to a few weeks during the middle of each season. More management attention should be directed to methods for spreading fishing effort evenly across each season.

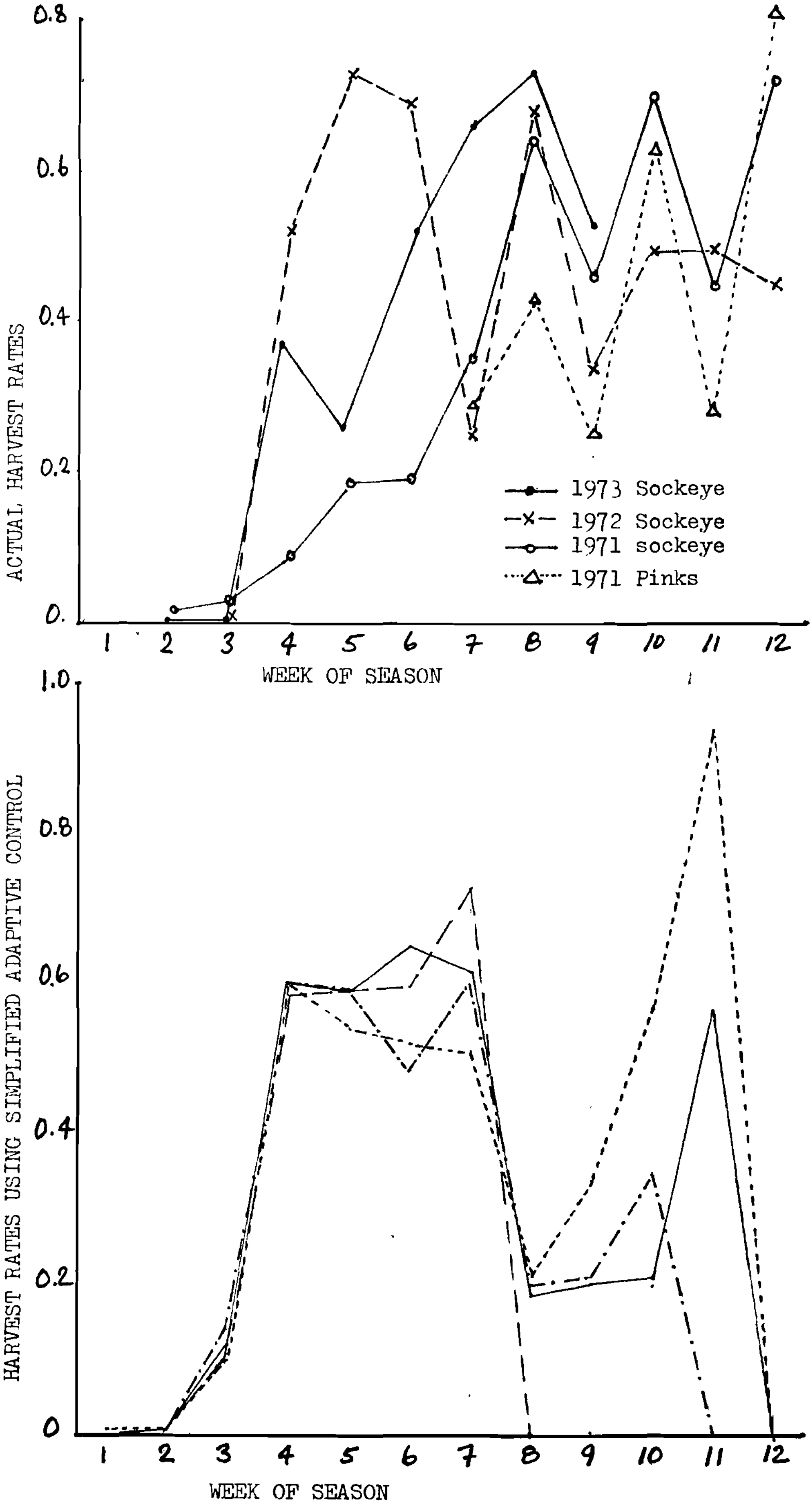

FIGURE 14 Observed seasonal variability in exploitation rates compared to expected variation using the preposed control system. Simulation results were chosen at random form a 500 year simulation-run; more extreme simulated patterns are obtained only when the desired pink and sockeye rates differ very markedly.