Trends in wild adult steelhead (*Oncorhynchus mykiss*) abundance in British Columbia as indexed by angler success

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Abstract: Intraregional similarities and interregional differences in wild steelhead (*Oncorhynchus mykiss*) abundance trends over time throughout British Columbia were identified using catch-per-angler-day (CpAD) as an index of abundance. This index was calculated using sport angler catch and effort data obtained by an ongoing mail-out questionnaire begun in the fiscal year 1967–1968. Despite high interannual variability in CpAD for individual rivers, its validity as an index of trends over time in wild steelhead abundance for geographic regions or watersheds is reinforced by similar trends yielded by both fishery-dependent and fishery-independent data. Time series methods generally could not build statistical support for the hypotheses that sudden regulation changes, or the gradual introduction over time of a catch and release philosophy, are generally important factors affecting trends over time in CpAD. This bolsters our confidence that the general patterns in mean CpAD over time within regions and watersheds reasonably index actual wild adult in-river steelhead abundance. We propose that the trends that we observe in wild steelhead CpAD are primarily driven by environmental influences. Some candidate environmental time series currently being considered and investigated are coastal upwelling, various ocean and atmospheric climate indices, freshwater discharge histories, and ultraviolet radiation.

Résumé : Les similitudes intrarégionales et les différences interrégionales des tendances de l'abondance de la truite arc-en-ciel anadrome (*Oncorhynchus mykiss*) sauvage en fonction du temps dans l'ensemble de la Colombie-Britannique ont été déterminées en utilisant les prises par pêcheur et par jour (PPJ) à titre d'indice d'abondance. Cet indice a été calculé à partir des données sur les prises des pêcheurs à la ligne et l'effort de pêche tirées d'une enquête permanente par questionnaires postaux qui a débuté au cours de l'exercice 1967–1968. En dépit d'une importante variabilité interannuelle du PPJ de mêmes rivières, la validité de cet indice des tendances temporelles de l'abondance de cette truite dans des zones géographiques ou des bassins versants se trouvent renforcée par des tendances semblables déterminées à partir de données dépendantes ou indépendantes de la pêche. Les méthodes fondées sur les séries chronologiques ne peuvent généralement pas appuyer statistiquement les hypothèses selon lesquelles les modifications soudaines de la réglementation, ou l'introduction graduelle de mesures de capture et de remise à l'eau, soient généralement des facteurs importants influant sur les tendances du PPJ. Cela appuie notre hypothèse selon laquelle l'allure générale temporelle du PPJ moyen au sein de régions où de bassins versants constitue un indice relativement fiable de l'abondance des adultes de la truite arc-en-ciel anadrome sauvage dans les cours d'eau. Nous suggérons que les tendances observées du PPJ des truites arc-en-ciel sauvages s'expliquent surtout par des facteurs environnementaux. On compte, parmi les séries chronologiques de facteurs environnementaux actuellement examinées pour utilisation, les remontées d'eau côtière, divers indices océaniques et atmosphériques, l'historique des écoulements d'eau douce et le rayonnement ultraviolet.

[Traduit par la Rédaction]

Introduction

Contemporary studies of the population dynamics of salmon (*Oncorhynchus* spp.) originating in rivers of the Northeast Pacific Ocean have focused on the influence of ocean climate on survival and abundance trends. Typically, changes in atmospheric or oceanic climate indices have been related to indices of change in the abundance of adult salmon returning to their natal rivers. Studies have considered environmental influences operating at annual up to decadal time

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Fig. 1. Map of British Columbia showing the five British Columbia management regions (1, 2, 3, 5, and 6) where steelhead are angled. The major snowmelt-driven watersheds are indicated, as are the Thompson, Dean, and Babine rivers, known for their desirable steelhead angling qualities. The four rainfall-driven regions are east coast Vancouver Island (ECVI), west coast Vancouver Island (WCVI), the lower mainland near Vancouver (LM), and the Queen Charlotte Islands (QCI).

scales (Francis and Hare 1994; Hare and Francis 1995; Mantua et al. 1997; Francis et al. 1998; Hare et al. 1999), often using time series methods on data collected from commercial fisheries. Fisheries scientists are also interested in how ocean climate affects the abundance of steelhead (*Oncorhynchus mykiss*) of the Northeast Pacific Ocean. Although some steelhead caught incidentally during marine commercial salmon fisheries appear on commercial landing slips (Shaw 1994), steelhead are mainly caught by freshwater sport anglers.

Catch and effort data have been collected for the steelhead sport fishery in British Columbia since the late 1960s using a questionnaire sent to randomly selected licensed steelhead anglers to poll their angling effort and success in the previous fiscal year (1 April to 31 March). This Steelhead Harvest Questionnaire (SHQ) is currently managed by the British Columbia Ministry of Fisheries. The SHQ has been conducted using essentially the same standardised format since the fiscal year 1967–1968, and the data collected have been used in conjunction with other methods, particularly creel surveys, to assess steelhead angling success (e.g., Hooton 1978; Ward and Wightman 1989).

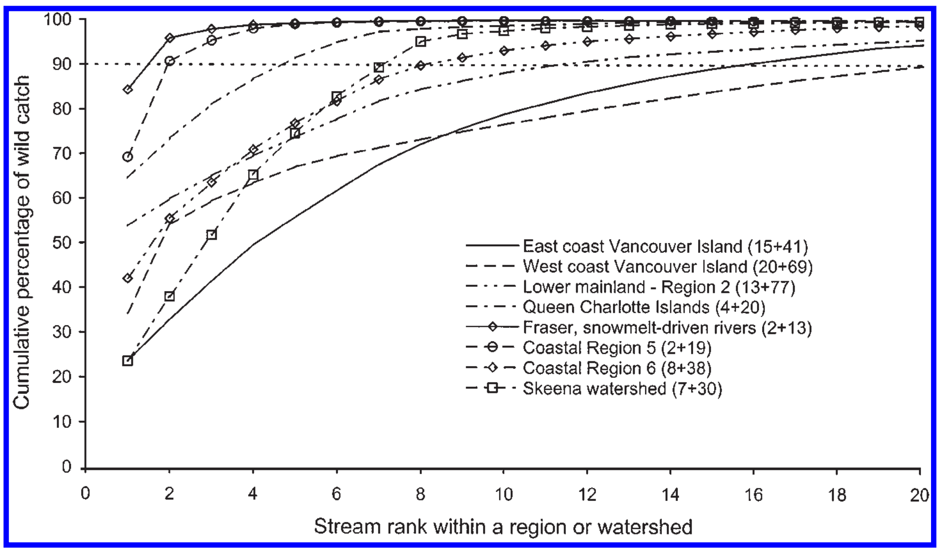
The SHQ constitutes a province-wide database of steelhead angler catches and effort, by river, that can be used to calculate an annual catch-per-angler-day (CpAD) as an index of adult steelhead abundance within each river. At face value, the 29 years of SHQ data appear to have provided useful information on trends in steelhead catch, effort, and abundance throughout British Columbia. However, the reliability of these data for this purpose has not been rigorously investigated. Factors potentially affecting the reliability of CpAD as an index of abundance range from changes over

Table 1. Summary of documented steelhead run types, winter run and (or) summer run, for British Columbia rivers (from Slaney et al. 1996).

Management region or watershed	Number of rivers in the region	Winter-run rivers	Summer-run rivers
Rainfall-driven regions or watersheds			
East coast Vancouver Island (Region 1)	15	15	3
West coast Vancouver Island (Region 1)	20	14	15
Lower mainland (Region 2, including the rainfall-driven tributaries of the Fraser River)	13	11	7
Queen Charlotte Islands	4	4	0
Snowmelt-driven regions or watersheds			
Snowmelt-driven tributaries of the Fraser River (Regions 3 and 5)	2	0	2
Coastal Region 5 (primarily the Bella Coola watershed and the Dean River)	2	2	2
Coastal Region 6 (excluding the Skeena, Stikine, and Taku watersheds and the Queen Charlotte Islands)	8	4	6
Skeena watershed (Region 6)	7	2	7

Note: The number of rivers in a region refers to those rivers responsible for ≈90% of the number of wild steelhead caught. The rivers that are responsible for the remaining ≈10% of wild catch are not considered in this table because of their small size, minor contribution to wild catch, or uncertain information about run type.

Fig. 2. Concentration indices for those rivers contributing to total wild steelhead catch from 1967–1968 to 1995–1996 for eight geographic regions or watersheds. The cumulative percentage of wild catch (caught and kept plus caught and released) starts with the river of highest rank, i.e., with the greatest contribution of wild steelhead, and ends with the river of lowest rank. In the legend, the first number associated with each region or watershed is the number of rivers contributing ≈90% of the wild catch for that region or watershed. The second number is the number of rivers aggregated to account for the last ≈10% of wild catch. The total number of rivers in any region or watershed is the sum of these two numbers. The lower mainland includes the rainfall-driven tributaries of the Fraser River. Coastal Region 5 includes the Dean River and Bella Coola watershed. Coastal Region 6 includes the Nass watershed.



time in licence fee schedules and in angler demographics (e.g., local anglers versus nonresidents), the reliability of anglers' recall regarding their catch success and angling effort reported to the SHQ, the introduction of regulations requiring that wild steelhead caught be released alive, the percentage of steelhead caught and released (prior to a regulatory requirement), and changes in sport anglers' methods and skills.

Smith (1999*a*) presented a detailed examination of the above-mentioned potential sources of bias affecting the reliability of wild adult steelhead CpAD as an index of abundance. In that report, Smith (1999*a*) concluded that licence fees, angler demographics, and angler recall were not important factors affecting the reliability of CpAD as a useful index of abundance. In this paper, we document only those features of the SHQ that communicate our confidence that the trends that we observe probably reflect environmental variability rather than biases in data collection, management actions, or changes in angler behaviour. Specifically, we (1) organise general trends over time in wild steelhead CpAD according to geographic regions or watersheds in British Columbia, (2) evaluate the reliability of CpAD as an index of trends in steelhead abundance, and (3) evaluate the effect of regulation changes and sport angler dynamics on CpAD or actual wild adult steelhead abundance.

We use time series methods (Hipel and McLeod 1994) to address points 2 and 3 above because of the autocorrelation typically observed in time series of fisheries catch and effort

Fig. 3. Time trends in the percentage of wild adult steelhead caught and released for the fiscal years 1967–1968 to 1995–1996 and for Regions 1, 2, 3, 5, and 6.

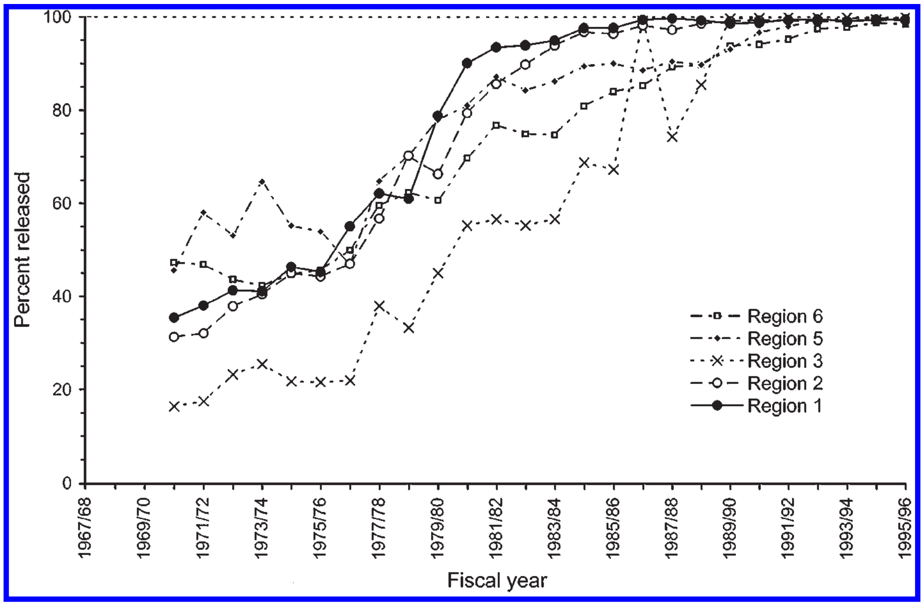


Table 2. Summary of wild adult steelhead daily bag limits gleaned from the British Columbia Sport Fishing Regulations Synopsis or its predecessors.

Year of regulation change	Region 1	2	3	5	6
1965–1966	2	2	2	3	3
1968–1969	4 or 8	8	10	10	10
1973–1974	1 or 2	2	2	2	1 or 2
1974–1975	1 or 2	1 or 2	2	2	1 or 2
1978–1979	1 or 2	1 or 2	2	1 or 2	1 or 2
1979–1980	1 or 2	1 or 2	1 or 2	1 or 2	1 or 2
1980–1981	1	1	1	1 or 2	1 or 2
1981–1982	1	1	1	1 or 2	1
1984–1985	1	1	1	1	1
1985–1986	**0**	**0**	1	1	1 or 2
1986–1987	**0 or 1**	**0**	1	1	1
1987–1988	**0**	**0**	1	1	1 or 2
1992–1993	**0**	**0**	**0**	1	**0 or 1**
1996–1997	**0**	**0**	**0**	**0 or 1**	**0 or 1**

Note: These limits are tabled according to the five British Columbia management regions (Fig. 1). These regulations do not express all angling rules in effect at a particular time for a particular river, since management actions such as Fisheries Public Notices can vary regulations in-season. These regulations also do not list voluntary conservation measures encouraged for certain regions or rivers in particular years, e.g., the promotion of catch and release. More detailed rules and regulations are summarised in Smith (1999*a*). A daily bag limit of zero (in bold) indicates regulatory catch and release.

data, as well as in those covariate series (e.g., percent catch and release, regulation changes) that we challenge to explain the trends that we observed over time in CpAD. We concerned ourselves here only with the longer time series of wild adult steelhead, although since about the early 1980s, hatchery steelhead can comprise an important portion of sport anglers' catch in some regions (Smith 1999*a*). Our study concludes that CpAD is a generally reliable index of regional or geographic trends in wild adult steelhead abundance and that biological interpretations of these trends have the potential to improve our understanding of marine and freshwater environmental influences on salmon and steelhead population dynamics.

Methods

SHQ

SHQ database

Each fiscal year (1 April to 31 March) since 1967–1968, the British Columbia provincial government randomly sent an SHQ to about 60% of anglers who had purchased a licence to angle for steelhead during the previous fiscal year. Over the years, responses concerning an angler's catch and effort were obtained from, on average, about 19% of steelhead anglers annually. The 1966–1967 Freshwater Fishing Regulations Synopsis reminded steelhead anglers to follow the recording protocols specified on their steelhead angler's licence. According to the 1967–1968 regulations "Every person 18 years of age and older, immediately after taking possession of a steelhead trout, shall punch out the appropriate perforation of the Steelhead Angler's Licence and write on the Steelhead Angler's Licence the date upon which the steelhead was caught, and the name of the river or water from which the steelhead was taken." The reporting requirements have changed little over the years, with perhaps the most significant change occurring in 1970–1971, when sport anglers were first asked to report on steelhead that they caught and released in addition to those that they caught and kept. The requirement for recording angling success has become less rigorous over the years, a change motivated primarily by the move away from retention fisheries for wild steelhead to initially voluntary, and then regulatory, catch and release of wild steelhead.

Four hundred and twenty-one rivers are identified in the SHQ database, each of which has an associated watershed code (Anonymous 1997) to identify its geographic location and corresponding management region (Fig. 1). Fiscal year had been chosen as the time period over which to summarise annual steelhead catch and effort data, since the sport fishery typically focuses on two separate

Fig. 4. Frequency distribution of the number of angler-days according to CpAD category for wild adult steelhead. This distribution was calculated using data for the fiscal years 1967–1968 to 1995–1996 and for Regions 1, 2, 3, 5, and 6.

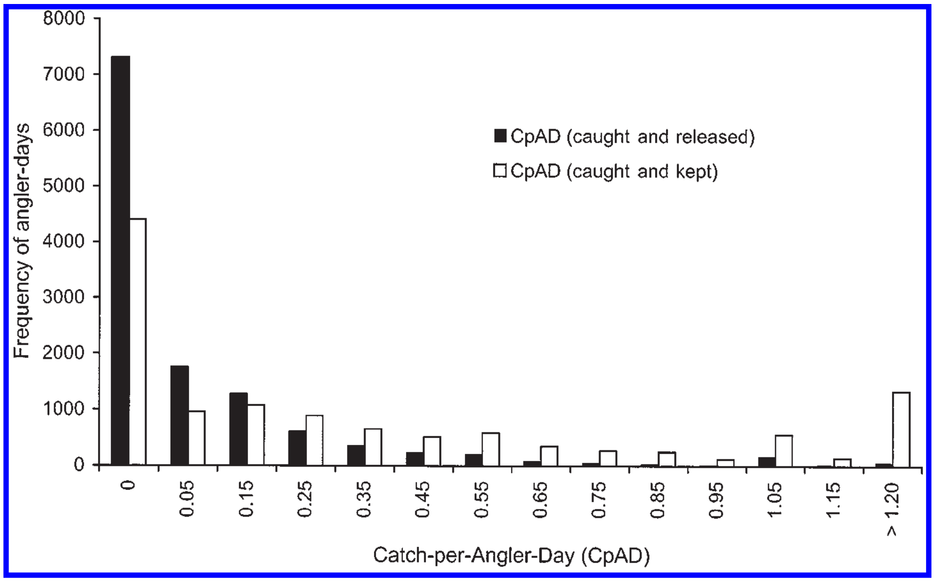


Table 3. Analysis of variance for a simultaneous time series analysis of standardised wild adult steelhead CpAD for those 46 rivers in British Columbia without missing data.

Summary					
Observations	1288				
r^2	0.24				
SE	0.73				
Analysis of variance	SS	df	Mean SS	*F*	*p*
Regression	212.53	3	70.84	133.77	<0.0001
Residual	680.02	1284	0.53		
Total	892.55	1287			
Parameter	Value	SE	*p*		
Intercept	0	—	—		
θ_1	0.14	0.05	<0.001		
ϕ_1	0.69	0.04	<0.001		
ϕ_5	0.07	0.03	<0.001		

Note: These 29-year-long series were once-differenced to remove trends over time, and then intraannual, interseries covariance was removed. The subsequent analyses identified a weak autoregressive term (θ_1) at a lag of 1 year, a moving average term (ϕ_1) at a lag of 1 year, and a weak moving average term (ϕ_5) at a lag of 5 years.

steelhead runs (Table 1). A summer fishery targets summer-run steelhead returning to freshwater generally between May and October, while a winter fishery targets winter-run steelhead returning generally between November and March (Burgner et al. 1992). Summer-run steelhead tend to be angled during the fall of the year that they return, while winter-run steelhead are angled during the winter and early spring months (Billings 1982). The SHQ does not discriminate between winter and summer runs within a fiscal year, and returning adults from one brood year can overlap adjacent calendar years.

Catch and effort information obtained using the SHQ is organised into data records that summarise individual angler responses into unique records. Each record documents the fiscal year to which the record pertains, the river in which the steelhead were caught, and the region where the sport angler resided. Each record reports the total number of days angled (angler-days) by all sport anglers with that particular year–river–residence definition and their total catch. Catch is partitioned into four categories: (*i*) wild steelhead caught and released, (*ii*) wild steelhead caught and kept, (*iii*) hatchery steelhead caught and released, and (*iv*) hatchery steelhead caught and kept. Hatchery steelhead can be distinguished from wild steelhead by their lack of an adipose fin. This allows the partitioning of catch, but not effort, according to whether it pertains to hatchery or wild steelhead.

Catch and effort data were used as officially recorded. In most analyses, wild catch refers to wild steelhead caught and released plus wild steelhead caught and kept. When analyses using effort data (angler-days) are reported, typically only data records with more than 100 angler-days were used. This reduced interpretation problems associated with small sample sizes. Some areas of the province had such low numbers of angler-days that they were not considered for analysis, i.e., the coastal mainland within Region 1 as well as the Stikine and Taku watersheds of Region 6 (Fig. 1).

Organisation of rivers

Initial analysis of wild adult CpAD indicated that comparisons within and among regions and watersheds would be most readily communicated if British Columbia's steelhead rivers were grouped by management region (Anonymous 1996) and according to whether their freshwater discharge regime was rainfall driven or snowmelt

Fig. 5. Left panels: wild adult steelhead CpAD (caught and kept plus caught and released) according to river (thin broken lines) for coastal, rainfall-driven regions of British Columbia. The thick solid line describes the mean annual CpAD for all rivers of that region. Right panels: same CpAD series but with each river standardised to a mean annual CpAD of zero with unit variance. Note the general similarity of trends among all regions until about 1990. All regions show an increase in CpAD from the late 1970s to the mid-1980s.

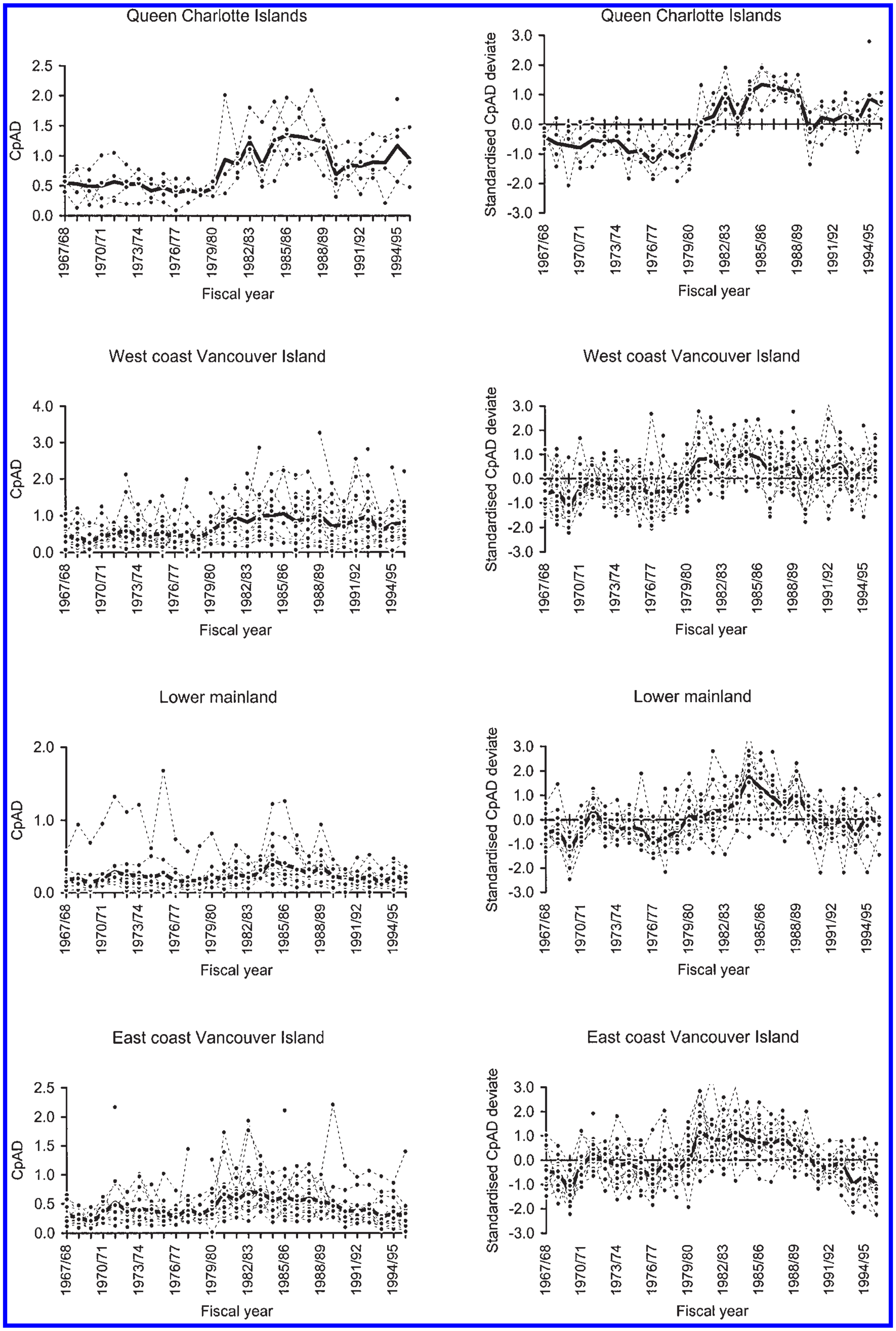


Fig. 6. Left panels: wild adult steelhead CpAD (caught and kept plus caught and released) according to river (thin broken lines) for inland, snowmelt-driven regions or watersheds of British Columbia. The thick solid line describes the mean annual CpAD for all rivers of that region or watershed. Right panels: same CpAD series but with each river standardised to a mean annual CpAD of zero with unit variance. Three rivers known for their particularly high values for CpAD are identified. All regions and watersheds show an increase in CpAD from the late 1970s to the mid-1980s. Coastal Region 5 includes the Bella Coola watershed. Coastal Region 6 includes the Nass watershed.

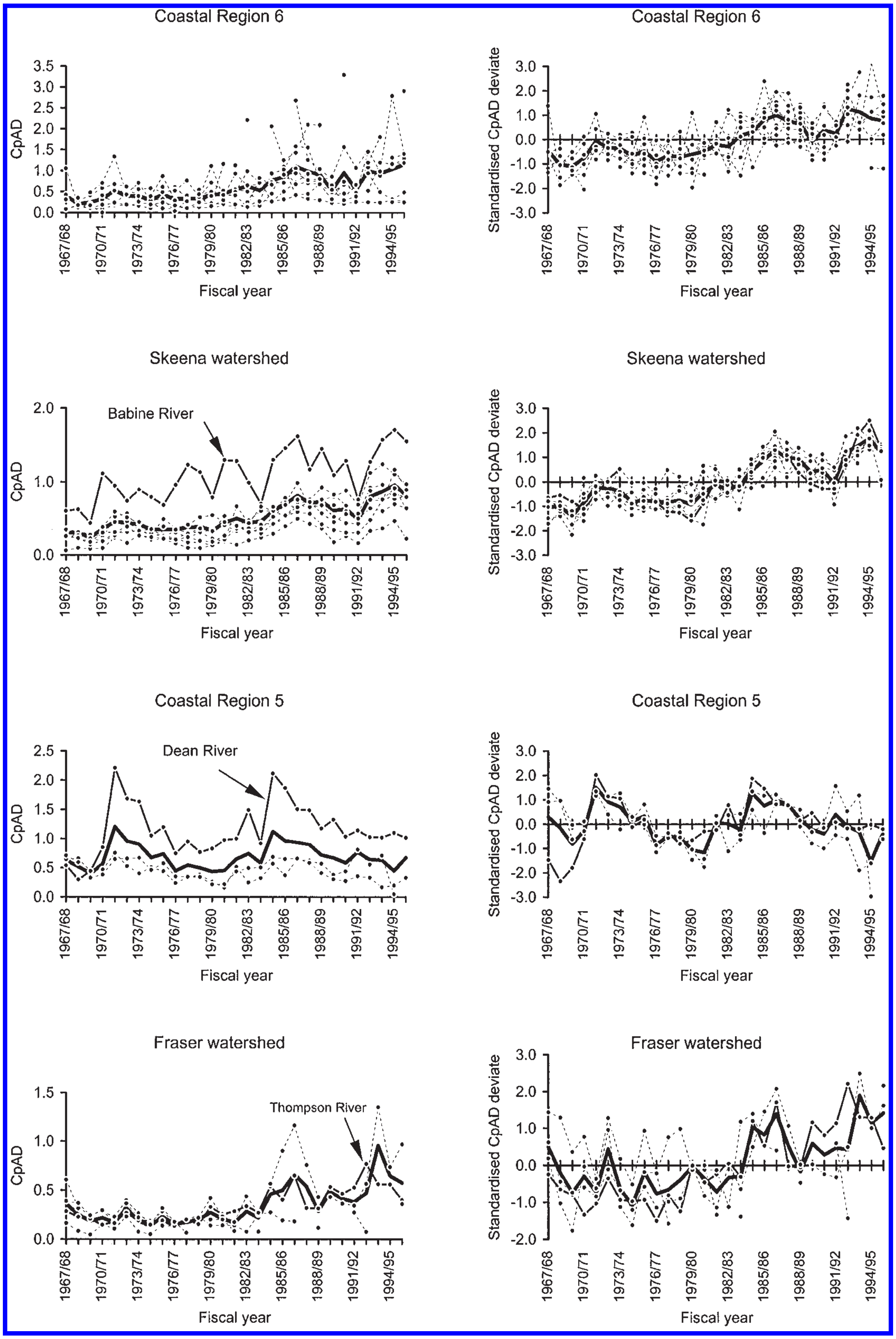
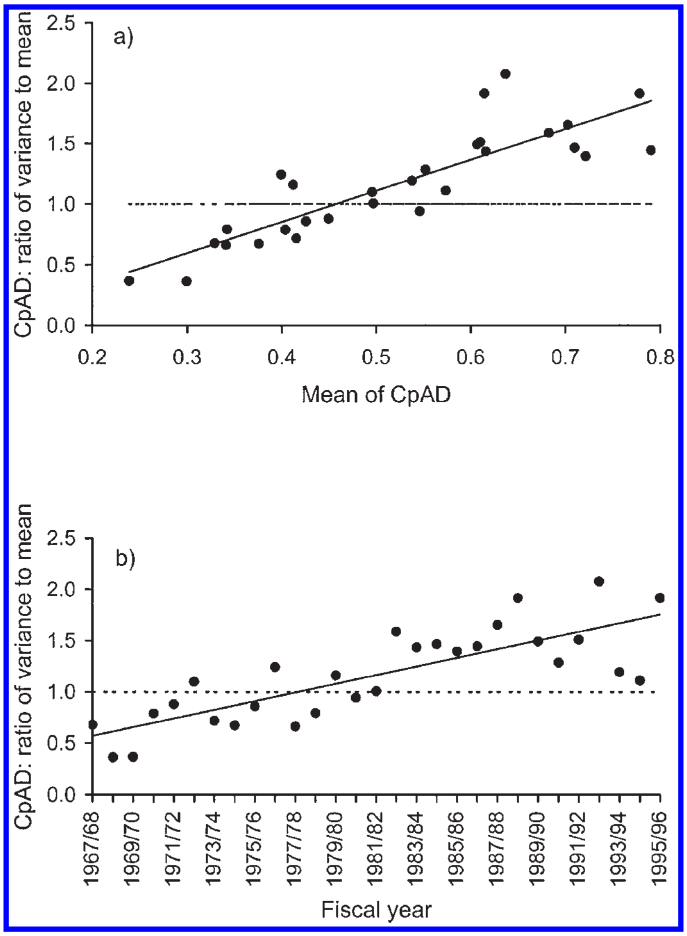


Fig. 7. Dispersion characteristics of wild adult CpAD, specifically the annual ratio of variance to mean (V[CpAD]:E[CpAD]). (*a*) V[CpAD]:E[CpAD] versus mean annual CpAD; (*b*) V[CpAD]:E[CpAD] versus fiscal year.



driven (Table 1; Fig. 1). Rivers of the rainfall-driven regions (east coast Vancouver Island, west coast Vancouver Island, the lower mainland near Vancouver, and the Queen Charlotte Islands) are generally small coastal rivers that flow directly to the ocean and generally have more winter-run than summer-run steelhead populations. Rivers of the snowmelt-driven regions are generally large inland tributaries to major mainstem rivers and generally have more summer-run than winter-run steelhead populations.

CpAD

Time series of annual CpAD were constructed for the major rivers within each of the above regions as follows. First, the total number of wild adult steelhead caught was summed over the fiscal years 1967–1968 to 1995–1996 for each river. Each river was then ranked in descending order of total catch. Those rivers of lowest rank contributing ≈10% to total catch were amalgamated to create a single aggregate series called the "complement." Second, for each river, an annual CpAD was calculated by dividing the sum of wild adult steelhead caught by the total number of angler-days, if the number of angler-days was more than 100. This procedure created as many as 21 time series (for west coast Vancouver Island) of wild adult steelhead CpAD for the various regions and watersheds (Fig. 2), one series for each named river, plus the complement. The minimum requirement of 100 angler-days for a CpAD calculation resulted in 34 of the 80 time series having at least one year where a value of CpAD was not calculated.

The 29-year-long time series of CpAD values were standardised in two steps. First, the CpAD values were square-root-transformed to remove dependence of the variance on the mean. Second, each transformed CpAD value was normalised by subtracting it from the mean for the series and then dividing by the standard deviation for the series. This standardisation facilitated direct comparison of patterns over time within and among rivers, and time series analyses (Hipel and McLeod 1994), unencumbered by differences in CpAD among rivers of different sizes and productivities.

Harvest regulations

Steelhead harvest regulations affecting an angler's daily bag limit have changed markedly over the years. Annual information on steelhead harvest regulations was obtained from the annually or bi-annually published British Columbia Freshwater Fishing Regulations Synopsis or its predecessors for all fiscal years since 1967–1968. Fisheries Public Notices can result in the regulations in effect on a particular river at a particular time being different from those reported in the Synopsis. Nevertheless, the generally steady movement over time from retention to catch and release fisheries, first through voluntary measures and then by regulation, is well represented by the daily bag limit regulations documented annually in the Synopsis (Table 2), as well as by the catch and release data collected by the SHQ (Fig. 3).

Time series analysis

Relevance to CpAD

Some analyses reported herein investigate relationships within and among time series using formal time series methods (Hipel and McLeod 1994) such as autoregressive integrated moving average (ARIMA) models, transfer function-noise (TFN) models, and intervention models. ARIMA models are designed for time series of values y_t where an observation at time t of n time periods is related to the central tendency of that series (i.e., the mean of series) and past observations. However, a time series of interest like CpAD can also be affected by external processes such as the percent catch and release in the current year or some past year. In such a case, statistical information is transferred from the ith of m covariate series ($x_{t,i}$, e.g., percent catch and release) to the series of interest (CpAD) using the TFN class of models. TFN models have their genesis in the notion that the information contained in one or more covariate series can explain similar variation in the series of interest at appropriate zero, negative, or even positive lags.

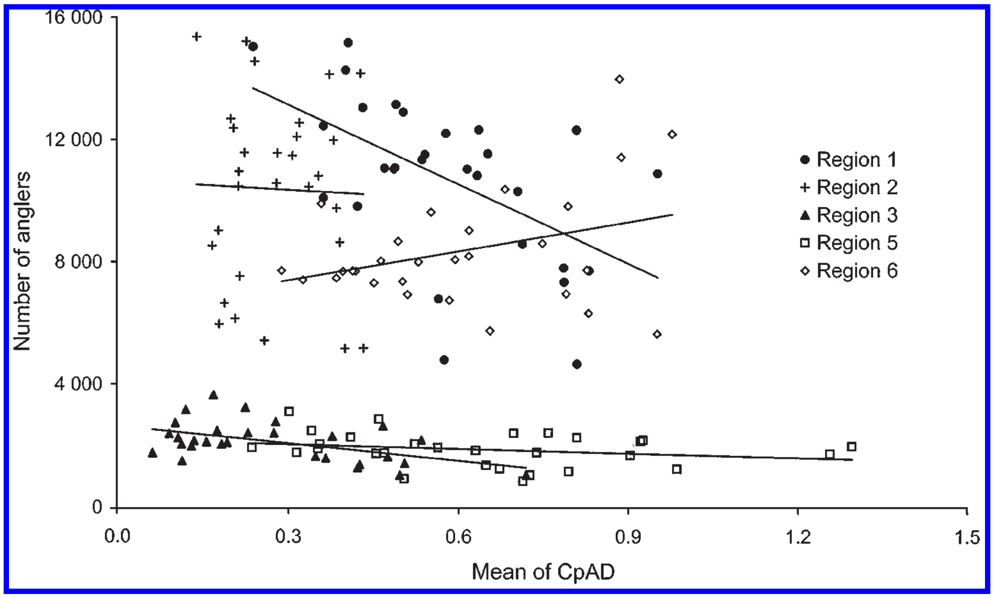
A useful extension of the TFN class of models is intervention analysis. Intervention analysis can identify nonrandom shocks to a time series, a shock being, for example, a sudden regulation change that might immediately change the mean of a time series. Shocks can be modelled in a variety ways and can be as simple as a step that might identify the effect of an abrupt and persistent regulation change. Other shocks might be pulse and decay processes that identify strong recruitment events or linear trends that identify steady increases or decreases in a series.

As an example, consider that a dramatic regulation change was imposed in a given year, say 1983, and that an analyst wanted to statistically test if there was a difference in the mean CpAD before and after the regulation change. The ith candidate intervention time series ($\xi_{t,i}$) would be

$$(1) \qquad \xi_{t,i} = 0, \; t < 1983$$
$$\xi_{t,i} = 1, \; t \geq 1983$$

and an associated coefficient (e.g., $\omega_{0,i}$) would estimate the change in mean CpAD attributable to that regulation change. Similarly, if an analyst wanted to evaluate the possibility of a linear decrease in

Fig. 8. The total number of anglers by region versus wild adult steelhead CpAD.



mean CpAD beginning in 1988, the following intervention series would be entertained:

(2) $\xi_{t,i} = 0, \ t \le 1987$

$\xi_{t,i} = (t - 1987), \ t > 1987.$

The modelling approaches discussed so far apply when there is only one time series of interest, y_t. For the questions addressed herein, much greater statistical power can be achieved by simultaneously analysing s similar time series, $y_{t,j}$, of standardised CpAD. The basic assumption is that each time series is a separate realisation of the same underlying process. Simultaneous analysis of several time series can facilitate the identification of processes that would be less likely to be identified using only a single series y_t .

Approximate maximum likelihood parameter estimates for the time series analyses performed in this investigation were obtained by minimising the sum of squares, SS,

(3) $$\mathrm{SS} = \sum_{j=1}^{j=s} \sum_{t=1}^{t=n} (y_{t,j} - y^*_{t,j})^2$$

where $y^*_{t,j}$ is the predicted value of $y_{t,j}$. The SS was calculated using only those values for the deviation $y^*_{t,j}$ calculated with nonmissing values of $y_{t,j}$ and $x_{t,i}$. Missing values were substituted with their expected values. The degrees of freedom were adjusted accordingly.

The decision to accept a particular model was based on how well it satisfied a posteriori diagnostics of model fit (Hipel and McLeod 1994; Burnham and Anderson 1998). An accepted model had to be parsimonious, i.e., all estimated parameters were statistically significant; the chosen model must have outcompeted other candidate models, and the accepted model must have reduced the error in the model to random Gaussian residuals. The choice of best model was assisted by the use of formal model selection techniques such as likelihood ratio tests and the Akaike information criterion (Burnham and Anderson 1998), where values for the negative ln likelihood (L) were calculated using

(4) $$L = n \ \ln\left[\sqrt{2\pi}\hat{\sigma}\right] + \frac{\mathrm{SS}}{2\hat{\sigma}^2}$$

where $\hat{\sigma} = \sqrt{\dfrac{\mathrm{SS}}{n - f}}$ and f is the number of estimated parameters.

Model identification was assisted by the use of CuSum plots (Murdoch 1979). CuSum plots are particularly useful tools in the exploratory phase of model identification. CuSum plots express cumulative deviations starting in year $t = 1$ relative to a chosen reference level for the series, often the series mean, and are useful for identifying tentative statistical relationships between a series of interest and a covariate series.

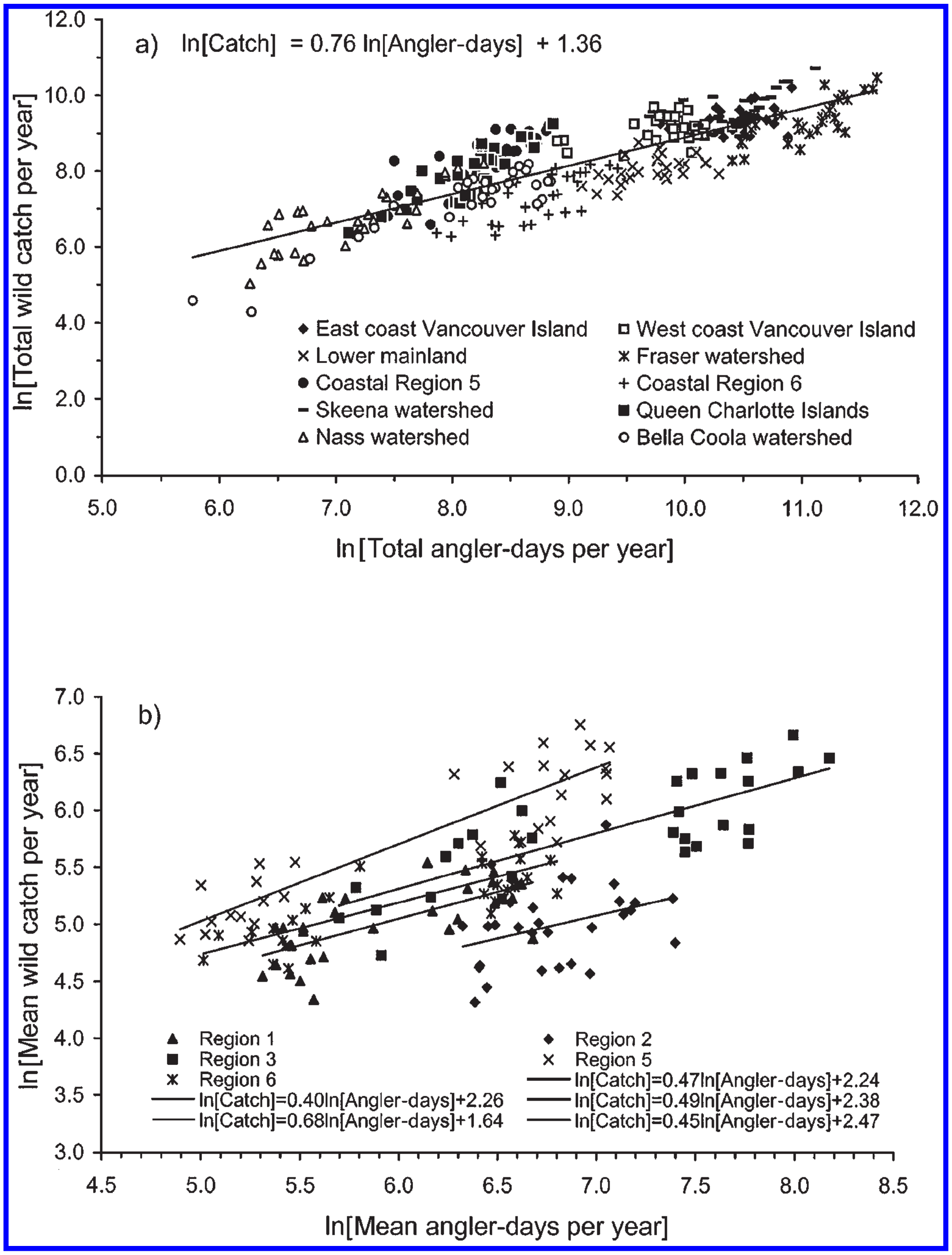
Application to CpAD

Time series for the 46 rivers without missing values for standardised CpAD were subjected to simultaneous analysis in an attempt to identify ARIMA parameters related to features of steelhead population dynamics common to all rivers (in-river dynamics) or features related to the manner in which catch and effort data were collected by the SHQ. All series were once-differenced (Hipel and McLeod 1994) to remove the long-term trends evident in the undifferenced times series. Intraannual, interseries covariance of the once-differenced values for CpAD was also removed by subtracting the annual means over all 46 series from the annual CpAD value for each river.

Attempts were also made to parsimoniously fit all candidate covariate series (i.e., regulation changes, percent catch and release) to the undifferenced series of standardised wild adult steelhead CpAD using TFN models. The actual covariate series were used for percent catch and release, but important regulation changes were treated as categorical intervention time series (see eq. 1). A step intervention series was included as an additional covariate series in all analyses to accommodate the change in the SHQ reporting protocol in 1970–1971 when anglers were first asked to include wild steelhead caught and released, in addition to those caught and kept, when responding to the SHQ. The regulation change and percent catch and release time series were considered to provide evidence of a correlation if any of those series satisfactorily explained the CpAD series for the regions to which they were applied. Candidate series were rejected as plausible explanations of the CpAD patterns when no statistical support for the fitted model could be achieved.

Not all regulation changes affecting total catch could be entertained in a statistically meaningful way, so only the most dramatic changes in the daily bag limit were considered. Specifically, for each region, only those changes in daily bag limit regulations re-

Fig. 9. (*a*) Logarithmic relationship between total annual wild catch and total annual effort (angler-days) according to region or watershed; (*b*) logarithmic relationship between mean annual wild catch and mean annual effort according to region.

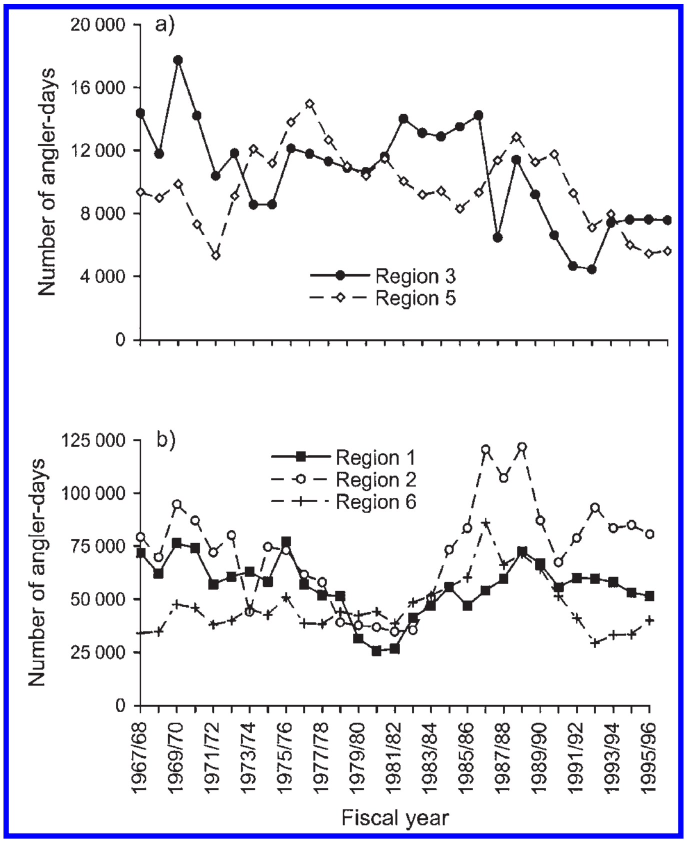


quiring mandatory release of all wild steelhead caught were considered (Table 2). In support of this decision, we note that the great majority of anglers caught and kept fewer than one steelhead per day (Fig. 4). Thus, we suspect that the potential for a lowering of the daily bag limit (even to zero steelhead per day) to affect the overall reliability of wild adult steelhead CpAD as an abundance index would be quite limited.

Sport angler dynamics

The reliability of CpAD as an index of trends in wild steelhead abundance over time can be seriously compromised by a change in the skill and methods of sport anglers over time. According to provincial steelhead managers, the community of anglers uses more specialized angling gear now than in the past, and access to angling rivers and locations has also increased over the years. Both of these factors can lead to over- or under-dispersion of angling success (CpAD) as well as to an overall change in steelhead catchability. However, the underlying mechanism (i.e., variability in angler skill versus variability in steelhead availability to anglers) cannot be distinguished with the data available to us. Nevertheless, if angling success is randomly distributed among anglers, then CpAD would tend to follow a Poisson probability distribution which has the dispersion characteristic that its variance equals its mean ($V[\text{CpAD}] = E[\text{CpAD}]$). Consequently, we interpret $V[\text{CpAD}] > E[\text{CpAD}]$ as overdispersion of angler success and $V[\text{CpAD}] < E[\text{CpAD}]$ as underdispersion of angler success. The former interpretation would suggest that the community of anglers is composed of a broad distribution of unsuccessful to successful anglers, while the latter interpretation suggests that the community

Fig. 10. Time trends in the number of angler-days for (*a*) Regions 3 and 5 and (*b*) Regions 1, 2, and 6.



of anglers tends to be similar in angling success. A change only in the dispersion characteristics of a community of anglers over time would not compromise the reliability of CpAD as an index of abundance, whereas an overall change in steelhead catchability would introduce a bias.

Alternate abundance indices

The most convincing way to demonstrate the reliability of an index of abundance is to compare its performance with other indices. We evaluated five indices of wild in-river adult steelhead abundance calculated independently of CpAD: (*i*) Keogh River (east coast Vancouver Island) fence counts, (*ii*) snorkel counts of escapements for certain west coast Vancouver Island rivers selected for assessment, (*iii*) escapement counts for snowmelt-driven Fraser River tributaries, (*iv*) the interception rate of wild steelhead by seine and net fisheries (as measured from landing slips submitted by the marine commercial salmon fleet) operating in the approach waters to the Skeena River, and (*v*) a gillnet test fishery at Tyee, near the mouth of the Skeena River, used to index the abundance of steelhead as they enter the river. These escapement indices were compared with CpAD as an index of wild adult steelhead abundance in these regions. Before use, these indices were standardised as was CpAD, i.e., they were expressed as deviations from a standardised mean of zero with unit variance, once the original series were log transformed to stabilise the variance.

Results

Patterns in wild adult CpAD

Time series of wild adult steelhead CpAD were organised according to the rivers' discharge regime (Northcote 1992), i.e., rainfall driven (Fig. 5) or snowmelt driven (Fig. 6). Segregation by precipitation regime reveals both intraregional similarities and interregional differences in abundance patterns. The rainfall-driven regions are characterised by a large number of rivers with high variability in CpAD among years. The snowmelt-driven regions have fewer rivers and tend to show less interannual variability in standardised CpAD. Trends tend to vary slowly across adjacent regions, with, for example, trends for rivers of the Skeena watershed being most similar to trends for adjacent coastal Region 6.

Time series analyses

In-river dynamics

Time series analysis of the 46 rivers not missing any values for standardised CpAD (Table 3) revealed a weak positive autoregressive term at a lag of 1 year (θ_1), possibly reflecting the tendency of the SHQ to sample the same late-winter run of steelhead in adjacent fiscal years. Such a correlation was anticipated by biologists familiar with the SHQ protocol and steelhead run timing. A strong, positive moving average term at a lag of 1 year (ϕ_1) leads us to suspect a density-dependent interaction between adjacent returning adult year-classes. If such an interaction exists, it would seem most likely to have originated during the juvenile, freshwater life history stage where there is competition between juvenile fish for food or habitat (Ward and Slaney 1993). A very weak, although significant, moving average term (ϕ_5) possibly reflects autocorrelation in wild adult steelhead abundance linked to a mean generation length of about 5 years.

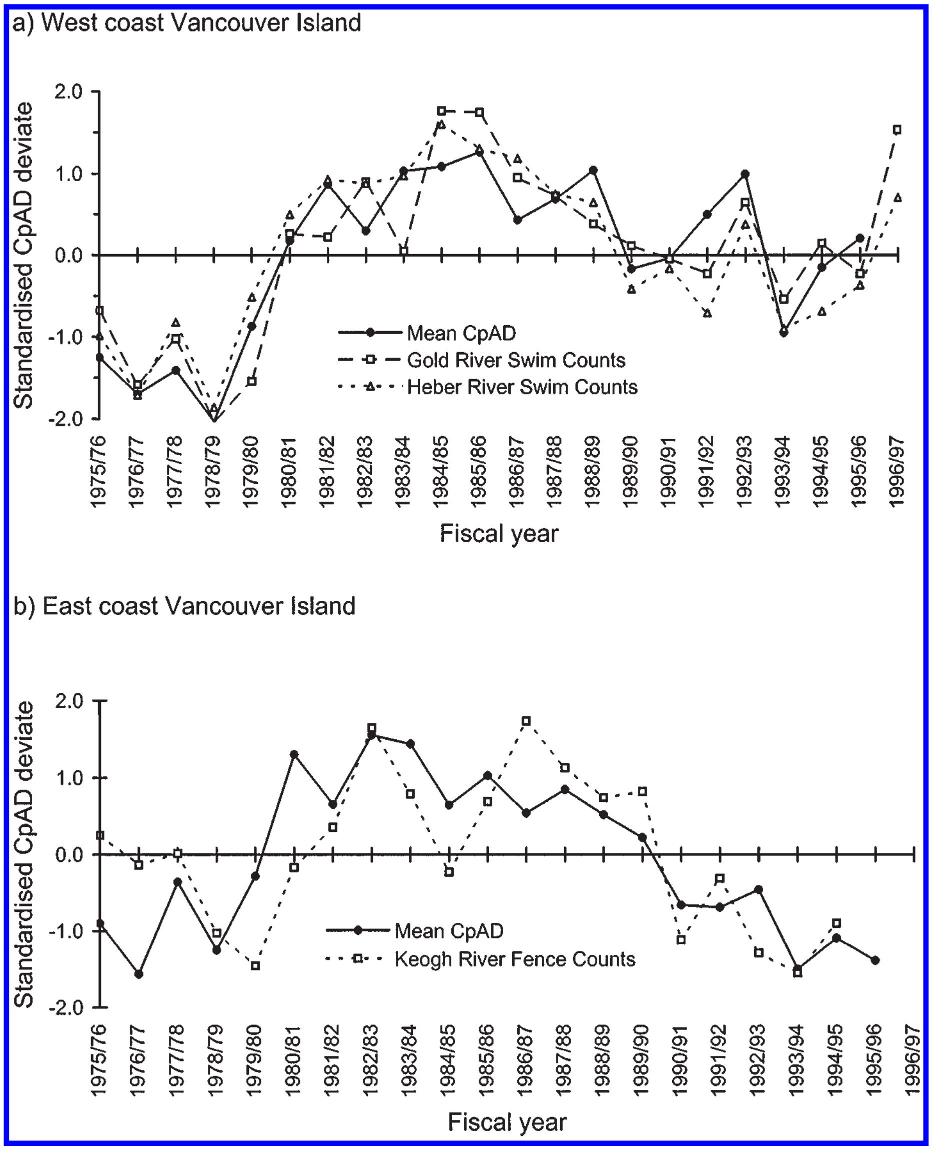
Effect of regulations on CpAD

Intervention analysis generally failed to attribute patterns in standardised CpAD to regulation changes. Step interventions were consistently ineffective in partitioning the CpAD series into segments distinguishable only by having different mean values of CpAD attributable to the catch and release rule in place at the time (Table 2). The one exception was an abrupt increase in mean CpAD for rivers of the Skeena watershed beginning in 1992–1993 following the introduction of a mandatory catch and release regulation, although the cause of that increase is subject to debate (see Smith 2000; Welch et al. 2000).

Effect of catch and release on CpAD

Catch and release can potentially lead to increased numbers of steelhead surviving to spawn, since caught fish are returned to the river to reproduce. This has the potential to cause an increase in adult returns a generation later if other factors such as habitat capacity do not limit the eventual number of adult returns. However, time series TFN analysis of the once-differenced series of CpAD and once-differenced series of percent catch and release indicated that in none of the five regions, nor for any assumed generation length ranging from 4 to 7 years, could trends in CpAD be statistically correlated with the implementation over time of catch and release. In all cases, $p > 0.05$, and in most cases, $p >> 0.05$. Additionally the pattern of correlation was random among regions and generations, reinforcing that no relationship between the percentage of wild steelhead caught and released and CpAD can be statistically identified.

Fig. 11. Comparison of standardised mean annual CpAD with log-transformed independent indices of wild steelhead abundance for (*a*) west coast Vancouver Island (1975–1976 to 1995–1996), (*b*) east coast Vancouver Island (1975–1976 to 1995–1996), (*c*) the Fraser watershed (1984–1985 to 1995–1996), and (*d*) the Skeena watershed (1970–1971 to 1995–1996). All series are standardised to a mean of zero with unit variance.



Sport angler dynamics

Distribution of CpAD

Our investigation of the factors affecting angler success (CpAD) revealed a strong and statistically significant ($p < 0.001$) tendency for the ratio of the variance to mean for CpAD (V[CpAD]:E[CpAD]) to increase with mean CpAD in each region (Fig. 7*a*). This leads us to interpret that in those years of better than average angling, the angling community was an overdispersed community of unsuccessful to successful anglers. This overdispersion may be due either to variability in angler skill among anglers or to variability in steelhead availability to anglers.

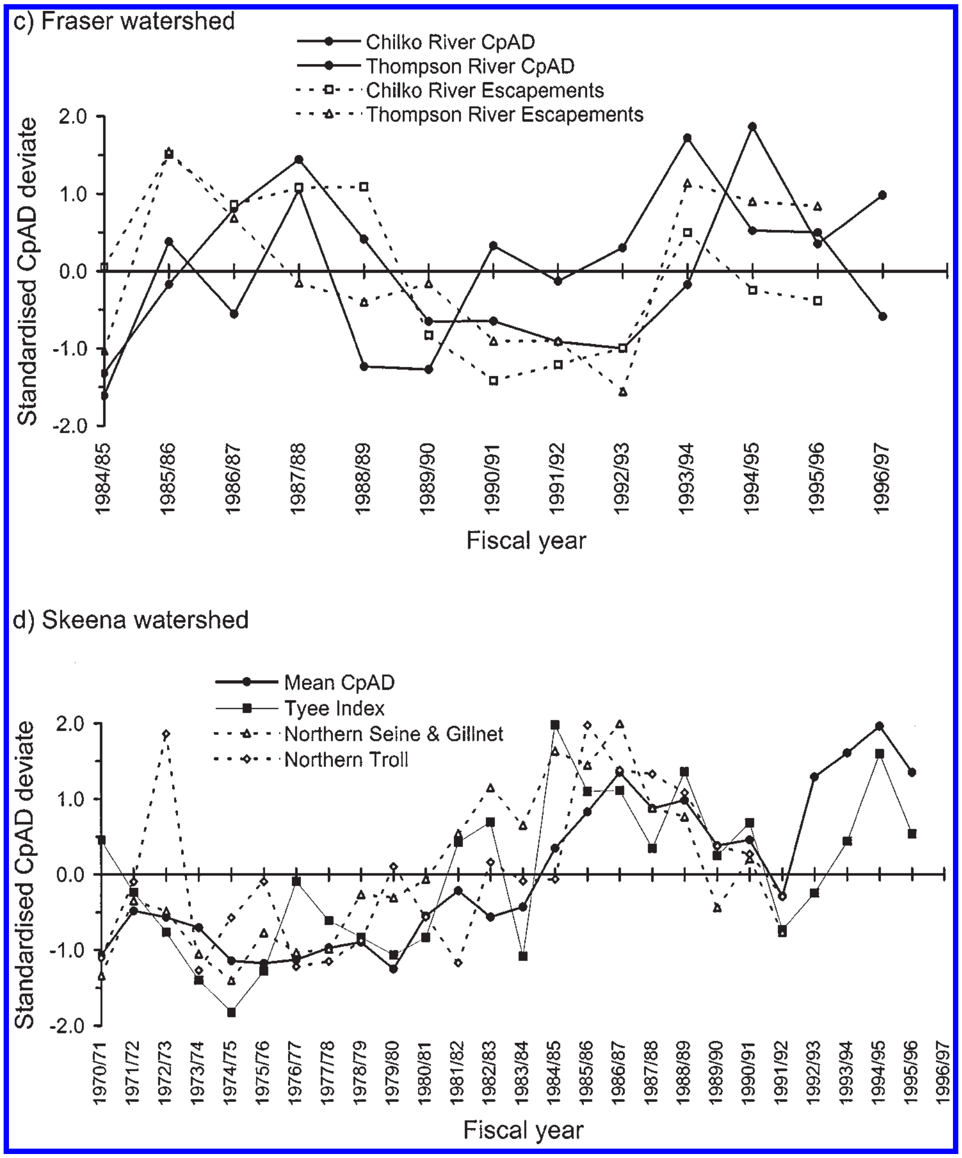
When V[CpAD]:E[CpAD] is reported as a function of fiscal year (Fig. 7*b*), there is a tendency for the ratio to increase over the years. This suggests that in the late 1960s, the angling community was somewhat homogenous in angling success but that in more recent years, angling success has become more heterogeneous. However, despite this strong evidence for either (*i*) diversification in anglers' skills and abilities or (*ii*) overdispersion of steelhead availability among anglers, it cannot be concluded that there has been a persistent overall change in mean catchability over time.

One explanation for the higher V[CpAD]:E[CpAD] ratios (Fig. 7) is that less skilled anglers are attracted to angling because they anticipate a good angling success (CpAD) when angling is generally good. However, there is no convincing evidence of a positive relationship between the total number of anglers and CpAD for any region (Fig. 8). Alternatively, overdispersion of variability in CpAD might result from increased variability in the effectiveness of bait, fishing gear, or angling techniques, access to the resource among anglers, or overdispersion of steelhead availability to anglers.

Catch versus effort

A logarithmic relationship between annual wild adult catch

Fig. 11 (*concluded*).



and annual effort (angler-days) for each region or watershed yields a slope of 0.76 (Fig. 9*a*). The slope being less than unity indicates that catchability in regions or watersheds with higher effort is consistently less than in regions with lower effort. When similar relationships are evaluated for mean annual catch and effort within each region, a comparable result is obtained (Fig. 9*b*). The slopes of these relationships also indicate that, within regions and watersheds, catchability during years of higher effort is less than in years of lesser effort. This result is evidence that increased competition among anglers reduces steelhead catchability and therefore also the catch expectation of individual anglers when angler effort is high.

The important implication of this result is that differences in effort (angler-days) among years can affect expected catch and consequently bias CpAD. This bias has the potential to affect the reliability of CpAD as an index of trends in steelhead abundance, if effort for any region or watershed also follows a persistent trend over time, as it appears to do for Regions 3 and 5 since the early 1980s (Fig. 10). We would advise that this potential bias be considered when judging patterns in CpAD for the Thompson and Chilcotin rivers, the two most important steelhead angling rivers of these two regions. Both rivers are designated as classified waters (Anonymous 1996) because of their desirable angling qualities. The Thompson River is among those few rivers in the province experiencing a very high number of angler-days and CpAD.

Alternate abundance indices

One factor that has the potential to bias CpAD as an index of steelhead abundance is the steady increase over time in the percentage of steelhead caught and released by anglers (Fig. 3). This bias would be caused by a gradual reduction in the "fishing-down" effect of catch and keep that in earlier years could have led to a significant drop in the number of steelhead in a river. Having contemporary angling rules that require all steelhead to be released alive effectively mimics sampling with replacement. Therefore, a satisfying way to evaluate the reliability of an index of abundance is to compare its performance with other, independent indices of abundance over the same time period. We compared CpAD as an index of wild adult steelhead abundance with other, independent indices of wild steelhead abundance for those four regions or watersheds with the most reliable information on CpAD (Fig. 11). We found the general trends in these alternate indices for the east and west coasts of Vancouver Island and the Skeena watershed to correlate well with the trends indicated by mean standardised CpAD, while the correlations obtained for the snowmelt-driven Fraser tributaries were weaker.

Vancouver Island

The high correlations observed between mean CpAD for west coast Vancouver Island and swim counts for the Gold River (r = 0.87 for 1975–1976 to 1995–1996) and Heber River (r = 0.89 for 1975–1976 to 1995–1996) provide strong evidence of the reliability of CpAD as an index of trends in wild steelhead abundance (Fig. 11*a*) for west coast Vancouver Island. Likewise, Keogh River fence counts show a similar pattern of variation over time with mean CpAD for east coast Vancouver Island (r = 0.70 for 1975–1976 to 1994–1995) (Fig. 11*b*).

Fraser River

Escapement counts of steelhead for the Thompson River (including its main tributaries) and the Chilko River of the Fraser River modestly correlate with CpAD (r = 0.41 for the Thompson River for 1984–1985 to 1994–1995; r = 0.48 for the Chilko River for 1984–1985 to 1994–1995) (Fig. 11*c*); however, there are assessment problems with these indices. One limitation is that the indices are available or comparable only for the years 1984–1985 and later. Reliable escapement counts for the Thompson and Chilko rivers are difficult to obtain because they are done from helicopters or fixed-wing aircraft in the spring when water levels and flow rates are high in these snowmelt-driven rivers.

Skeena River

High correlations were obtained between CpAD and catch-per-day-fished (CpDF) for the commercial northern seine and gillnet net fisheries (r = 0.78 for 1975–1976 to 1991–1992) and the northern troll fishery (r = 0.69 for 1970–1971 to 1991–1992) when compared over the same years. Likewise, when both CpAD and the Tyee test fishery index are standardised over the same period, a high correlation between the indices is obtained (r = 0.70 for 1970–1971 to 1995–1996) (Fig. 11*d*). Steelhead CpAD and CpDF differ sharply after 1992–1993 because of a change in policy and methods for managing the number of steelhead surviving the commercial and sport fisheries (Smith 1999*a*).

Discussion

Our analyses affirm the general reliability of CpAD as an index of mean trends in wild adult in-river steelhead abundance. However, we caution that CpAD is most reliable when it is calculated using data from several or all rivers in a region or watershed. A single value for CpAD is a much less reliable index of abundance than an average value (see Figs. 5 and 6). Consequently, little weight should be given to individual values or trends that occur over only a few years. The similarity of trends of fishery-dependent and fishery-independent indices of abundance with wild adult CpAD for four important regions and watersheds (Fig. 11) suggests that wild adult CpAD provides a useful index of changes over time in actual wild in-river adult steelhead abundance. With the possible exception of the Skeena watershed beginning in 1992–1993, our analyses found no evidence that the sudden introduction of a catch and release regulation in a river or watershed increased mean CpAD. Likewise, we could garner no statistical support for the hypothesis that the gradual implementation of a catch and release philosophy over time, or changes over time in sport anglers' methods or skills, seriously affected the reliability of CpAD as an index of trends in wild adult in-river steelhead abundance.

We could find no statistical evidence for a cause–effect relationship between wild adult CpAD and a regulation change. The reason for this may be that the daily catches of the vast majority of anglers were well below the daily bag limits prior to the implementation of mandatory catch and release (Fig. 4). However, exceptions to this interpretation may occur for the Dean, Babine, and Thompson rivers, which experience among the highest values of CpAD in the province (Fig. 6). We caution that interpretation of trends for these rivers would be precarious. These rivers are among those designated as classified waters (Anonymous 1996) because of their desirable angling qualities. They stand out as having particularly high values for CpAD when compared with other rivers in their region. As previously mentioned, the trend in wild adult CpAD over time for the Thompson River is possibly biased by a decreasing trend in effort (angler-days) over time (Fig. 10).

The apparent lack of impact of steelhead angling regulations on the long-term trends in wild adult in-river steelhead abundance may be due to those regulations having been based on consultation with the sport angling client (Hooton 1985; Anonymous 1996, p. 5) and not on biological assessments of the potential consequences of regulations. Smith (1980) commented on how steelhead anglers in general appreciate the entire angling experience, although they are motivated in part by anticipation of successful angling (Fisher 1997; Smith 1999*b*). Thus the desire to satisfy the sport angling client has heavily influenced sport angling regulations in North America. Managers have relied on consultation or questionnaires designed to measure the mindset of their client when developing sport angling policy and regulations (Duttweiler 1976). Detailed quantitative projections of the potential effects of regulations are rarely conducted (Smith 1999*b*). Arguably, we might have been more successful in relating changes in steelhead abundance over time to regulation changes if those changes had been accompanied by strategic sampling or experimentation to measure their impact, although we now suspect that any effects of those regulations would be small when compared with environmental influences.

We were also unable to build statistical support for the hypothesis that the gradual increase over time in percent catch and release was responsible for increased steelhead abundance, as might have been anticipated by both steelhead managers and steelhead anglers. If there was such an effect, it is conceivable that our analyses lacked the power to detect it because of the quality of the catch and release information provided by the SHQ, the high interannual variability in CpAD, and environmental forcing of the observed trends. It is also possible that prior to catch and release becoming common practice, in-river steelhead abundance was at or near the habitat's capacity, and the release of live fish had little potential to affect future adult recruitment. Nevertheless, catch and release remains a sound conservation philosophy that should assure that steelhead are not overexploited in years of low steelhead abundance. It is quite possible that the gradual voluntary implementation of this philosophy, mainly in the 1980s, and regulatory catch and release have sustained some populations.

Based on the general patterns that we observe for CpAD, we draw the general inference that steelhead abundance in British Columbia has changed similarly among rivers within regions and watersheds but has changed variably among regions and watersheds. The different patterns over time among regions or watersheds tend to follow a continuum, with adjacent regions or watersheds being most similar (Figs. 5 and 6). A major distinction can also be seen between rainfall-driven regions and snowmelt-driven regions or watersheds (Figs. 5 and 6). The generally small rivers of the rainfall-driven regions tend to show much lower covariance in CpAD among rivers than do the generally larger rivers of the snowmelt-driven regions, particularly the rivers of the Skeena watershed. Overall, the mean trends in steelhead abundance (Figs. 5 and 6) appear to be generally consistent with our current understanding of the decadal-scale changes in the abundance of salmon in the Northeast Pacific (Francis and Hare 1994; Hare and Frances 1995; Mantua et al. 1997; Francis et al. 1998; Hare et al. 1999), an understanding that is elusive, given the high degree of noise and autocorrelation in environmental time series. Interpretations of observed trends in steelhead abundance in relation to ocean and freshwater climate have begun to emerge from our work and the work of others (Busby et al. 1996) and in companion (Smith 2000; Smith and Ward 2000; Ward 2000) and competing (Walters and Ward 1998; Welch et al. 2000) papers.

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