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THE INFLUENCE OF EXTREME WATER TEMPERATURES ON MIGRATING
FRASER RIVER SOCKEYE SALMON (*ONCORHYNCHUS NERKA*) DURING
THE 1998 SPAWNING SEASON

by

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ABSTRACT

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During the summer of 1998 record low water levels and record high water temperatures were predicted and occurred throughout the Fraser River watershed. All stock groups of sockeye salmon (*Oncorhynchus nerka*) were exposed to these conditions during their annual spawning migration. Records kept from previous years indicated a high likelihood for en route and spawning ground losses to all stock groups exposed to these conditions. We review these records, provide estimates of both en route and pre-spawn mortality in 1998, and comment on our ability to forecast migration success with existing models and knowledge. Mechanisms used to monitor temperature and discharge are documented and a retrospective evaluation of our in-season forecasts of Fraser River conditions is provided. We also describe events that occurred during the migration, and estimates of the stress levels and reproductive success of selected stocks, once they had arrived at their spawning grounds. The literature is reviewed as it pertains to migration success and opinions are provided to explain the events of the summer of 1998 in the Fraser River. Findings are summarized in an Executive Summary.

RÉSUMÉ

Macdonald, J.S., M.G.G. Foreman, T. Farrell, I.V. Williams, J. Grout, A. Cass, J.C. Woodey, H. Enzenhofer, W.C. Clarke, R. Houtman, E.M. Donaldson, and D. Barnes. 2000. The influence of extreme water temperatures on migrating Fraser River sockeye salmon (*Oncorhynchus nerka*) during the 1998 spawning season. Can. Tech. Rep. Fish. Aquat. Sci. 2326: 117 p.

Pour l'été de 1998, on avait prédit des étiages records et prévu que les températures de l'eau seraient les plus élevées jamais enregistrées; c'est ce qui a été observé dans tout le bassin hydrographique du Fraser. Tous les groupes de stocks de saumon rouge (*Oncorhynchus nerka*) ont été exposés à ces conditions au cours leur migration de fraye annuelle. Les registres des années précédentes ont montré une probabilité élevée de pertes pendant la montaison et dans les frayères pour tous les groupes de stocks exposés à ces conditions. Nous examinons ces registres, estimons la mortalité en cours de montaison et avant la fraye en 1998, et analysons notre capacité de prévoir la réussite de la migration avec les modèles et les connaissances dont nous disposons. Les mécanismes utilisés pour surveiller la température et les débits sont documentés et nous fournissons une évaluation rétrospective de nos prévisions en cours de saison sur les conditions prévalant dans le Fraser. Nous décrivons également les phénomènes qui sont survenus pendant la migration, et présentons des estimations du degré de stress et du succès de la reproduction de certains stocks après leur arrivée dans les frayères. Nous analysons la littérature en ce qui concerne le succès de la migration, et présentons des points de vue visant à expliquer les phénomènes de l'été 1998 dans le Fraser. Les résultats sont résumés dans un sommaire à l'intention de la direction.

EXECUTIVE SUMMARY

Water levels and temperatures in 1998 were severe throughout the Fraser River system. Such conditions have caused problems to spawning migrants in past years (Migration Condition Section). A program to provide in-season 10-day forecasts of water levels and temperatures was initiated 4 years ago following a recommendation from the Fraser Report (1994). Forecast reliability and usefulness at predicting migration conditions in the Fraser watershed in 1998 were examined and found to be dependent on watershed location. We also examine the influence of several factors on migration conditions, including rainfall levels in the upper basin, forest harvesting in first and second order tributaries, summer artificial cooling flows from the Skins spillway and the McKinley Lake siphon, and large lakes throughout the basin.

After spawning ground information was compiled in the fall of 1998, a comparison of Mission and upstream estimates revealed a negative discrepancy of 3,393,800 sockeye salmon, with discrepancies contributed from every run of the season (En route Mortality Section). This is the largest loss on record for a single season. An analysis of the relationship between upstream and Mission estimates for each stock group since 1977 indicates that our estimation techniques provide an expected pattern (positive correlation with a slope of 1), but absolute reliability declines with increasing run size. An analysis of the residuals indicates that flow rates and water temperatures on the migration route can explain much of the discrepancy pattern.

Seven of eight Fraser sockeye salmon stocks in 1998 had average or below average pre-spawning mortality rates (PSM) when compared to data records since 1974 (Pre-spawning Mortality Section). With the exception of the early Stuart run, PSM estimates do not support the hypothesis that upstream migration in the Fraser River was stressful to the point of precipitating catastrophic mortality among spawners. Correlations between PSM across years for different stocks within the same run timing group (e.g. Summer run) suggests that PSM in stocks that enter the Fraser River at about the same time may be influenced by a factor(s) common to these stocks. For six of eight sockeye stocks, mean Hells Gate water temperature explains only a small amount of the variation in PSM rates. Thus the data does not generally support the hypothesis that Hells Gate water temperature can be used to predict PSM. A case can be made for using temperature to predict PSM in early Stuart sockeye (but this relationship relies heavily on the outlying 1998 data point) and the Adams stock (but overall low PSM to date make this unnecessary). More data points for years with extreme water temperatures will be needed to confirm the utility of this relationship. Across all eight stocks, earlier peak run timing was associated with increased PSM. However, peak run timing only explains a small amount of variation in PSM, except for Chilko and late summer runs. Consequently, the data for Early Stuart or summer run sockeye does not support the hypothesis that peak run timing is a useful indicator of PSM losses. Also, it is difficult to make pre-season predictions. A re-analysis of Gilhousen's multiple regression analysis with recent data indicates that a combination of peak run timing at Hells Gate and mean Hells Gate temperatures account for only a small portion of the variation in PSM observed. As a result, these indicators have limited utility for predicting potential pre-spawning mortality losses in Fraser sockeye. We recommend a reconstruction of the run-timing data prior to 1974 using commercial and test fishery records to make use of 26 years of pre-spawning mortality and Hells Gate temperature data from 1948 to 1973. Additional indicators, particularly from the ocean environment, should be examined for their potential utility in explaining PSM. It is also important to note that our analyses to date have assumed a linear relation between stressor (temperature or timing) and fish response, despite evidence to suggest that physiological impairment may only occur as threshold conditions are exceeded.

During their up-river migration, sockeye salmon orient to the shore (Migration Behaviour Section) but show distinct changes in behaviour during rising Fraser River water levels and when exposed to in-river gillnet fisheries. The turbidity during rising water promotes surface orientation, while nets cause the fish to move from shore and towards the bottom, frequently into higher current areas. Rising water temperature, even to the extreme levels seen in 1998, has no apparent effect on the migration orientation or location.

The 1998 sockeye salmon carcass counts at the Mission facility, when presented as a percent of the run size, are the largest on record (Sockeye Carcass Counts Section). The largest mortality was associated with mid-summer in-river gillnet fisheries and the highest river temperatures, and occurred in coincidence with the early Stuart and summer stock groups. In contrast, substantial observation efforts throughout the Fraser Basin by fisheries officers, local residents, and scientific staff did not indicate large en route mortality further upstream. Based on the timing of observation records, the mortality and abnormal behaviour that was observed was likely a result of distressed early Stuart fish that were eventually lost en route. Observation reports consistently emphasized that 1997 was a far worse year than 1998 in regards to abnormal behaviour and counts of moribund fish. There were many reports of distressed and lost chinook salmon in 1998 from locations throughout the watershed, but there is reason for particular concern for stocks in the Thompson watershed.

We found little evidence for arrival timing delays on the spawning grounds in response to the extreme conditions along the migration route. There was little annual variation in migration timing (Life Span Analysis Section). However, once on the spawning grounds several indicators, including length of time to death, recovery from tagging operations, and estimates of spawning success indicated that both the early Stuart and (to a lesser extent) the Horsefly runs were in poorer condition than the other runs. Net mark incidence was not unusually high in 1998.

Laboratory examination of gill, liver, kidney, and head-kidney samples from Horsefly salmon, in the late stages of migration, indicated no unusual levels of damage. A detailed histological comparison of fish with and without obvious external damage indicated the limited value of superficial observations of fish condition on the spawning ground. A review of the subject emphasizes the role of temperature, density, and length of exposure to diseases as being critical to understanding the relationship between disease and migration-related mortality (Disease Observations Section).

Four stress parameters and three reproductive parameters, recorded during the last stages of migration and during spawning of Horsefly sockeye, indicated that fish were suffering from chronic stress associated with up-river migrations (IRND's) and acute stress associated with the extreme water temperatures and low water levels in the Horsefly watershed (cortisol) (Stress Section). High lactate levels in some migrants suggested higher than expected energy expenditure considering the water levels, and some sources of energy (e.g. glucose) were being used prematurely. Conditions experienced in 1998 are expected to have a serious impact on sockeye reproductive potential. While reproductive parameters followed a predictable pattern, declining estradiol and increasing 17,20P with the onset of maturity and spawning was an indication that both fertilization success and hatching rates were impaired as a result of high temperatures during migration and spawning among early Horsefly spawners. A laboratory study using early Stuart sockeye suggests that high temperatures can reduce plasma sex hormone concentrations.

From a physiological perspective, the results of the observations reported in this document suggest that the high water temperatures adversely affected the Fraser River sockeye migrants in 1998 (Stress Section). Diseases associated with high temperature and stress associated with disease can adversely affect swimming performance. High temperatures can also increase metabolism reducing energy use efficiency, and reducing a fish's ability to recover from fatigue and stress, a situation made particularly acute when accompanied with even mild hypoxia. The hazards of hypoxia during migration also include potential impairment of sexual maturation, but the physiological and behavioural processes are poorly understood.

INTRODUCTION

FRASER RIVER SOCKEYE SALMON STOCKS

Each summer and fall adult sockeye salmon return to over 150 natal stream, river, and lake spawning areas in the Fraser River watershed to spawn and to bury their fertilized eggs in protective gravel environments. The name of the stream, river, or lake of spawning has been used to designate the stock of sockeye reproducing at that location. Thus, we refer to the Gates Creek, Chilko River, and Cultus Lake sockeye simply to distinguish one stock from another. Stocks are defined as being reproductively isolated.

The adult fish that return to spawn in each stream or lake of the watershed are fish that incubated there as eggs/alevins. The individual stocks vary from one another in body size, arrival timing, and other physiological and behavioral traits apparently due to the adaptations required for survival in their natal spawning stream, rearing lake, and river and marine migrational environments. Measurable differences exist between the stocks at several DNA loci that have been examined (Beacham et al. 1995). These differences are likely due to genetic drift that has occurred over long periods of reproductive isolation and simply verify that the observed differences between stocks are associated with restricted gene flow between populations.

Once the nature of the homing and reproduction of the stocks became known in the early 1900's, the designations of the stocks by their spawning area became the norm. These stock names are used in the management of the aboriginal, commercial, and recreational fisheries that target adult sockeye salmon on their coastal and river migrations to natal spawning areas. Migrational timing and behavioral traits in the coastal and river areas overlap for many of the sockeye stocks within the Fraser River watershed. For management purposes, all stocks have been assigned to one of four stock groups (also called run timing groups) based on arrival timing and river migrational behaviour as follows:

- Early Stuart: Sockeye returning to the tributary streams of Takla Lake, Trembleur Lake, and Middle River in the Stuart Lake watershed in the far northwestern portion of the Fraser system. These fish are the earliest to migrate each year, entering the lower Fraser River between late June and late July (approx. June 25-July 25) immediately upon arrival in the Strait of Georgia.
- Early Summer: This group is composed of a large number of stocks that enter the lower Fraser between mid-July and mid-August, usually without delay in the Strait of Georgia. Included in this stock group are sockeye that spawn in the Upper Pitt River, Chilliwack Lake, Nahatlatch River, Fennell Creek, Raft River, Upper Adams River, Seymour River, Scotch Creek, Eagle River, Anstey River, Gates Creek, Taseko River, Bowron River, and Nadina River. Several other streams in the watershed support smaller populations of sockeye or those that return on only one or two cycles.
- Summer: The "summer-run" or "mid-summer" stocks are (generally) large runs that spawn in middle and upper Fraser River tributaries. These include the Chilko River and Lake; Horsefly River and Mitchell River in the Quesnel Lake watershed; Stellako River; and Late Stuart sockeye that spawn in Middle River and Tachie River and in tributaries to Trembleur and Stuart lakes in the Stuart Lake watershed. These stocks normally

migrate into the lower Fraser River between late July and early September immediately after arrival in the Strait of Georgia, although short-term delays are not uncommon.

- Late: Sockeye that spawn in a number of lower and middle Fraser tributaries. These include Widgeon Slough, Cultus Lake, Weaver Creek, Big Silver Creek, Harrison River and Birkenhead River in the lower Fraser; Lower Adams River, Little River, Lower Shuswap River, Middle Shuswap River and tributaries and beach spawning areas of Shuswap Lake; and Portage Creek in the Seton-Anderson Lake watershed. These stocks arrive in the Strait of Georgia between early August and mid-September. However, they normally follow a different life history pattern from the above three "summer-run" stock groups by delaying in the Strait of Georgia from 1 to 6 weeks before migrating upstream. Length of delay of each stock varies annually. Migrations in the lower Fraser peak in late August (Birkenhead, Big Silver), mid-to-late September (Lower Adams, Lower Shuswap) or late September to mid-October (Weaver, Portage, Cultus, Harrison, Widgeon).

Most Fraser River sockeye stocks display regular 4-year cycles of annual abundance variation. In extreme cases, abundance among the four cycle lines may vary by over three orders of magnitude (1,000X). These cases are typified by Adams River sockeye and are termed "cyclical dominance" patterns. In 1998, the stocks that were expected to provide the largest returns were Chilko River and Lake, Quesnel Lake (Horsefly and Mitchell), Lower Adams River/Little River, and Lower Shuswap River. Smaller but significant returns were forecast for the Early Stuart, Seymour, Scotch, Stellako, Late Stuart, Birkenhead, and Weaver stocks. The 1998 cycle line was the largest of the four lines for many years peaking in abundance in 1990 (22 million fish). The forecast for 1998 was for a return of 11.2 million fish.

THE INFLUENCE OF EXTREME PHYSICAL CONDITIONS ON MIGRATING SALMON

Programs to investigate the influence of environmental conditions in the Fraser River on sockeye salmon (*Oncorhynchus nerka*) spawning migrations have been in existence for over 30 years. Initiatives have been generated by the Department of Fisheries and Oceans (D.F.O.) and the International Pacific Salmon Fisheries Commission (IPSFC) under a number of titles and as a result of a number of factors. Recently, two reviews, the Pearce-Larkin Report and the Fraser Report, have provided the impetus to consider this issue a priority. The central theme to 30 years of investigations is the belief that a link exists between the health and fitness of spawning stocks of Fraser River salmon and the water temperatures and river discharge experienced by the fish along the migration path. Most vulnerable are the Fraser stocks returning in June, July, and August, including the early Stuart, early summer, and summer stock groups. Late groups are also likely influenced by severe river conditions. When conditions are severe, spawning success can be impaired due to (a) en route mortality, (b) failure to spawn despite arrival at the natal streams (pre-spawn mortality), or (c) reduced gamete viability. Stock productivity is threatened, rebuilding initiatives are delayed, and in-season fishery management becomes exceedingly difficult.

The first report of a Fraser River run failure is provided by accounts from Hudson's Bay Company records at Fort St. James in 1899 and 1900 (Cooper and Henry 1962). More recently, we have recorded pre-spawning and/or en route mortality for most Fraser stocks in association with high river discharge and/or water temperature. One of the earliest reported en route losses occurred in 1958 when approximately 322,000 fish or 7.6 percent of the overall

sockeye run failed to return to their spawning grounds as a result of extremely high water temperature (IPSFC 1959; Clarke et al. 1994). High water temperatures were also implicated in pre-spawning losses to many runs in 1961 (31%-86%) (IPSFC 1962). Losses in other years (1955, 1960, 1964, 1982, and 1997), particularly to the early Stuart stocks, have been associated with passage problems in the lower river during high discharge events (losses range from 51 to 96%) (Macdonald and Williams 1998). En route losses have been attributed to (a) migration passage impairment, caused by high discharge events (Macdonald and Williams 1998) or high water temperatures (Major and Mighell 1966; Cooper and Henry 1962), (b) elevated rates of energy depletion and exhaustion as a result of high discharge or warm water temperature (Gilhousen 1980; Clarke et al. 1994; Rand and Hinch 1998), and (c) accumulated stress during migration (Williams et al. 1996). Pre-spawn mortality has been attributed to cumulative stress, run timing, and elevated water temperatures in the Fraser River or on the spawning grounds (Gilhousen 1990; Williams et al. 1996). Pathogenic bacteria (*Flexibacter columnaris*) and parasites prevail during periods of elevated water temperature (Williams 1973; Williams et al. 1977). Despite similar causes, en route and pre-spawn mortality are not necessarily linked (Gilhousen 1990), but both may foretell gamete viability impairment and intergenerational failure (Herunter et al. 2000).

PURPOSE OF THE REPORT

The purpose of this report is to examine the possible effects of Fraser River environmental conditions on mortality of sockeye salmon from each of the stock groups during the 1998 spawning migration (Fig. 1). A portion of the discrepancy between sockeye numbers estimated at the Mission hydroacoustic facility (Fig. 2) and numbers counted on the spawning grounds may be attributed to severe migration conditions and associated en route losses. This report will address many hypotheses and predictions, and provide background physiological, ecological, and behavioural information pertinent to sockeye salmon during their spawning migration. Information is presented in sections and includes the following: (a) a description of the physical conditions faced by the fish during migration; (b) the results of our attempts to forecast these conditions; (c) the magnitude of the discrepancy between Mission and upstream estimates with an assessment of our estimation techniques and the influence of physical conditions on the discrepancy pattern; (d) a description of pre-spawn mortality in 1998 with a comparison to previous years and predictions from published methods; (e) an assessment of the influence of river features on migration behaviour; (f) a presentation of carcass enumeration reports from several sources; (g) reports of sockeye behaviour on the spawning ground; and (h) a review of the influence of stress during migration on the incidence of disease, stress, and reproductive condition with preliminary results from recent research.

MIGRATION CONDITIONS – 1998

Lower Fraser River discharge in 1998 was calculated from water height data collected electronically on a real-time basis from Qualark Creek (Fig. 2). These data correlate very strongly with similar data collected annually since 1912 by Environment Canada near Hope, B.C. ($P < 0.01$). Fraser River water temperatures were provided by 10 real-time data loggers placed at sites throughout the Fraser Basin (Fig. 2). Data loggers were factory calibrated and readings were checked with spot temperature measurements on a regular basis to ensure data quality. River temperature data has been collected electronically since 1993 at most sites, but more extensive databases were available from Hells Gate (1941-1998) and the Horsefly River

(1961-1998). Pre-1993 data were collected with chart recorders or manually with thermometers, and were used in this report to provide a long-term historic perspective. Winter water temperatures are available from many sites but are not presented in this report.

Water discharge in the lower Fraser River during the 1998 sockeye migration period was near or below the 86 year minimum flows (Fig. 3). Between early July and mid-September flows declined from 4,000 m³/s to 1,000 m³/s in sharp contrast to 1997 when flows exceeded 9,000 m³/s for several days in July. Winter snow pack estimates in 1998 in the Fraser Basin were below average as precipitation in the interior fell as rain due to the warm winter conditions. An early and warm spring depleted the snow pack storage (MoELP web site, www.env.gov.bc.ca/wat). Throughout the late spring and early summer, fisheries staff reported receding lake levels in the upper basin and many tributaries had extremely low water.

Years in which river discharge is below average are frequently years during which water temperatures are above average. This is particularly true in July when inter-annual variation in flows are larger than other times of year (Table 1). Mean daily water temperatures at Hells Gate were the highest on record for most days during the summer of 1998, frequently exceeding 20°C in late July and early August (Fig. 4, database in Appendix A). Ranked by mean summer water temperature, 1998 was much warmer than any of the previous 51 years (Fig. 5a). There were 61 days between July 1st and September 15th when temperatures exceeded 18°C, a temperature at which sockeye salmon swimming ability is impaired (Brett 1982, 1995) (Fig. 5b). The warmest water temperatures occurred during the period in which the early Stuart, early summer, and summer sockeye stock groups were in the river. Throughout the summer, water temperatures were at least 1°C and frequently >4°C above normal (Fig. 6). The largest daily water temperature variation from average occurred during the period in which the early Stuart run was in the lower river (mid-July).

Table 1. Correlation coefficients describing the relationship between Fraser River discharge and water temperature at Qualark Creek during the months that sockeye salmon return to spawn. Data from 1942 to the present were used.

JULY	AUGUST	SEPTEMBER	JULY-SEPTEMBER
- 0.748	-0.375	-0.256	-0.454

Other water temperature monitoring locations in the watershed also recorded abnormally warm temperatures throughout the summer. Residents in the Horsefly area reported temperatures as being “unusually warm” and stream water levels as being “unusually low” this year (Environmental Watch Bulletin No. 10, 1998). Temperatures in the Horsefly River reached daily maximums of 23°C during mid-August as a large run of summer run sockeye arrived to spawn (Fig. 7a). These temperatures (only daily maximums are available in the historic databases) were warmer than previous years since 1961, a year that had temperatures similar to 1998. Cooling flows (approx. 8.0°C) released by a siphon from McKinley Lake (constructed in 1969) began on August 31st and were effective at cooling McKinley Creek for the first 2 weeks of September by approximately 2.0°C (measured at the confluence with the Horsefly River) (Fig. 7b). By late September, siphon and lake surface temperatures had equilibrated (D. Lofthouse, Fisheries and Oceans Canada, personal communication). Siphon discharge had little temperature moderating influence beyond its

confluence with the Horsefly River and was not detected at our data logger site near the town of Horsefly (Fig. 7b).

In accordance with agreements between Alcan Aluminium, the Province of British Columbia, and the Department of Fisheries and Oceans, water is released from the Nechako Reservoir (through the Skins Spillway) to provide prescribed flow levels and maintain temperatures below 21.7°C in the Nechako River upstream of its confluence with the Stuart River during the period July 20 to August 15 (Kemano Completion Project Review 1994). Nechako (at Prince George) and Stuart River temperatures exceeded 22°C in late July during the early Stuart run migration (Figs. 2 and 8). Nechako temperatures were 3 to 4°C warmer than most previous years (records kept since 1993) and at least a degree warmer than temperatures in 1994, a year in which water temperatures may have caused en route losses. Water temperatures at Vanderhoof (Nechako River above the confluence with Stuart River) and Shelley (Fraser River above the confluence with Nechako) were somewhat lower. Releases from the Skins Lake spillway began on July 6 and within 1 week, the flows at Vanderhoof had more than doubled from 115 m³/s to 253 m³/s. Prior to these releases, Vanderhoof temperatures were approximately 1.5°C warmer than those in the Stuart River at Fort St. James, but had dropped by July 12th to become identical. (Note that water temperatures at many other locations in the upper basin also began decreasing on about July 10 in response to atmosphere cooling). By the end of July, the Vanderhoof temperatures were approximately 1.5°C cooler than those at both Fort St. James and Prince George, while by mid-August when the releases had stopped, all three temperatures were approximately the same. It appears that releases from the Skins Lake Spillway resulted in temperature decreases of approximately 1.5°C at Vanderhoof and kept maximum values below the prescribed 21.7°C threshold. Though these decreases were not as large further downstream, due to input from the Stuart River and atmospheric heating, they helped moderate downstream temperatures from becoming warmer than they would have been otherwise.

Other locations in the Fraser River watershed were also recording extremely high water temperatures in the summer of 1998 (Fig. 2). Temperatures in the Thompson watershed were approximately 20°C (Fig. 9) during late August to late September when the Adams River run and several other Late Summer stock groups were in the system. While historic data records extend back no further than 1993 at most of these sites, the 1998 runs experienced the warmest conditions on record, including 1994 when run failures were noted in several stocks (Clarke et al. 1994).

Twenty-one 10-day river temperature and flow forecasts were issued during the period June 29 to September 7 using models (Foreman et al. 1997; Quick and Pipes 1976) developed at the Institute of Ocean Sciences, the University of British Columbia, and Triton Environmental Consulting. In general, our forecast accuracy is highly dependent on the accuracy of 10-day weather predictions that are obtained from the Mountain Weather Service office of Environment Canada. As expected, the ability to forecast the weather generally deteriorates with the length of the forecast. This deterioration extends to our flow and river temperature forecasts. For instance, an atmospheric cooling trend that is forecasted but does not materialize will produce inaccurate river predictions.

The accuracy of the temperature forecasts at Qualark and Ashcroft were averaged and root-mean-square errors (rms) were calculated over each 10-day period and plotted as functions of time (Fig.10). With the exception of three periods in mid-July and one in late

August, the rms values for Qualark are less than 1°C and comparable to the error calculated in 1997 (0.88°C). While the 1997 forecasts at Ashcroft were also accurate (0.88°C), the analogous values in 1998 were not as good because the model that forecasted temperature was consistently between 1°C and 3°C cooler than actual. This problem is attributed to the assumption that the mixed layer depth in Kamloops Lake was deeper than its actual value. The heat transferred from the atmosphere to the surface of the lake will only penetrate to a prescribed depth, the mixed layer depth, and thus warms a volume of water determined by the product of this depth and the surface area. The increase in lake temperature as a result of a specific amount of atmospheric input varies inversely with the volume of water and the mixed layer depth. An accurate estimation of this depth is necessary to understand the influence of atmospheric input on the temperatures at lake outlets.

The flow forecasts were carried out in collaboration with Professor Michael Quick and his Mountain Hydrology Group at the University of British Columbia. When compared with observations collected by the Water Survey of Canada Branch of Environment Canada at Hope on the Fraser River and Spences Bridge on the Thompson River, the root-mean-square error in our predicted flows over the period July 4 to September were 5.6% and 8.3%, respectively. This is considerably better than the analogous rms errors of 16% and 13% in 1997 when there were numerous heavy rain storms that were not accurately forecasted by Environment Canada.

Several factors influence Fraser River flows and temperatures during the salmon migration season. Snow pack accumulation over the previous winter is obviously important, though generally most of this snow has melted by the time the river flows peak in late May and early June, well before sockeye enter the river. Weather conditions throughout the summer play the most important role. The influence of five environmental variables on water temperature as expressed by correlation coefficients were calculated at several sites throughout the Fraser watershed, using measurements taken during the summers of 1993 through 1997. The results are summarized in Table 2.

Table 2. Correlation coefficients between water temperature and solar radiation (S), dew point temperature (T_d), wind speed (W), air temperature (T_a), and flow magnitude (F) at eight sites in the Fraser River watershed. Data from 1993 to 1997 were used.

River	S	T_d	W	T_a	F
Fraser at Shelley	0.04	0.24	-0.14	0.38	-0.38
Nechako	0.13	0.41	-0.15	0.46	0.28
Quesnel	-0.11	-0.05	-0.13	0.06	-0.68
Chilcotin	-0.03	0.23	-0.34	0.47	0.33
S. Thompson at Chase	0.03	-0.03	-0.15	0.25	-0.56
N. Thompson at McLure	-0.04	0.04	-0.36	0.31	-0.56
Nicola	0.02	0.33	-0.12	0.68	0.07
Fraser at Hope	-0.03	-0.05	-0.14	0.19	-0.60

It is clear that the importance of each variable with respect to its influence on water temperature varies considerably with location in the Fraser Basin. Water temperatures at

Shelley, Quesnel, Chase, McLure, and Hope are negatively correlated with the flow while those in the Nechako, Chilcotin, and Nicola rivers are positively correlated. As summer progresses, increases in flow arise predominantly from precipitation. The negative correlations indicate a cooling due to rainfall at higher elevations. The positive correlation between flow and water temperature for the Nechako River is particularly noteworthy, as between July 20 and August 15, the Nechako River flows are regulated by releases from the Skins Lake Spillway that are intended to cool the river. When our regression is restricted to just this period, the correlation between flow and water temperature changes to -0.206. The releases did cool the river in 1993-97, which was also the case in 1998. However, the positive correlation for the longer regression indicates that flow increases outside the July 20 to August 15 period were bringing warmer water to the river. This could reflect the influence of warm rainfall or increased input from warm tributaries such as the Stuart River. Similarly, for the Chilcotin and Nicola rivers, a warming with increased flows must reflect warmer rain than was found in the watersheds of the other tributaries and headwaters.

With the possible exceptions of the Quesnel River and the Fraser River at Hope, water temperature is strongly correlated with air temperature (Table 2). The low value at Quesnel probably indicates the moderating influence of Quesnel Lake where, dependent on wind direction, seiches and upwelling activity may influence the temperatures of Quesnel River as suggested by large daily/weekly temperature fluctuations (Fig. 11). The low correlation at Hope indicates that as the river increases in size, air temperature has less influence on water temperature than other factors further upstream. It is interesting to note that at all sites, the largest correlations are either with air temperature or flow. Correlations with wind, while weak, were consistently negative, denoting enhanced evaporative cooling with increasing wind speed. Correlations with solar radiation are (surprisingly) weak at all locations.

The strong negative correlations between river temperature and flow again emphasize the importance of rainfall in cooling most of the watershed. In 1997, several heavy rainstorms in July were instrumental in keeping river temperature low and flow high. There were no similar events in 1998, which probably contributed to the high river temperatures. Though the preceding detailed analysis has not yet been extended to include all data for 1998, correlations between Hope flows and Qualark temperatures have been calculated using data since 1942 (Table 1). Strong negative correlations, particularly in July, are reminders that fish passage problems are not restricted to years with high Fraser discharge.

Since the 1960's forest harvesting in riparian areas has been cited as being responsible for summertime temperature increases in first and second order streams (Levno and Rothacher 1967). Models have been developed that predict harvesting impact based on amount of stream exposed to solar radiation, and streams discharge (Brown 1970). Research that followed confirmed the validity of Brown's models and identified stream exposure as the primary factor influencing stream temperature (Beschta et al. 1987). More recently, other factors such as stream depth, a watershed feature frequently reduced after forest harvesting (Hartman and Scrivener 1990), have also been implicated in water temperature increases (Adams and Sullivan 1989). Forestry-induced temperature impacts may have serious implications to the health of local fish populations. However, there is a growing body of evidence suggesting there may be minimal cumulative temperature effects on third order streams as a result of riparian harvesting on upstream first and second order systems (Doughty et al. 1991; Caldwell et al. 1991). As a heated stream re-enters a forest, a number of factors affect a cooling process, including radiant heat loss back to the atmosphere and groundwater input (Macdonald et al. 2000). Full temperature recovery may occur in a few

hundred metres (Macdonald, unpublished data) or in several kilometres (McGurk 1989). Groundwater will have greatest moderating influence during dry/low flow periods such as the late summer, when biological susceptibility to high temperature is likely to be greatest. Cumulative (downstream) effects are further dependent on mixing relationships downstream, in that the larger and warmer the lower order tributary the greater its influence on the third order stream. As stream size increases, the influence of exposure to solar radiation declines (Table 2). The importance of mixing ratios is taken to an extreme if the watershed contains a lake. Large lakes are expected to have unique effects on lake outlet temperatures that will overwhelm upstream processes due to large volumes, surface areas, and seiches.

The summer of 1998 had the warmest air temperatures on record for the southern interior of the province and above normal, but not record breaking temperatures, for the region north of Prince George. July was the hottest month ever for several locations in southern B.C., breaking records that were set in 1958 (another El Niño year) at several of these sites (Gary Myers, Environment Canada, personal communication). The likelihood that the 1998 low Fraser River flows and high temperatures were associated with the 1997-98 El Niño has illuminated the need to provide a long-term forecasting capability associated with El Niño/Southern Oscillation (ENSO) events. Using the Japan Meteorological Agency classification of ENSO events, reconstruction of equatorial sea surface temperatures prior to 1949 (see also http://www.coaps.fsu.edu/~legler/jma_index1.shtml and Meyers et al. 1999) showed average Fraser River flows at Hope after warm, cold, or neutral ENSO winters as evident in Fig. 12. This time series starts in 1912. As they usually bring more precipitation (snow in mountains) over the winter, cold (La Niña) events are clearly seen to produce higher flows in the following summer. Warm events have slightly higher flows earlier in the spring (earlier snow melt) and smaller flows throughout the rest of the summer (as experienced in 1998). The summers following El Niño events also have significantly less flow than summers following cold and neutral ENSO conditions.

A similar analysis of the Hells Gate spot temperature time series indicates that through most of July and early September, river temperatures are warmer after El Niño events (Fig. 12). However, from approximately August 1 to August 20, the river temperatures are virtually the same, regardless of the preceding ENSO conditions.

Average Fraser River discharge at Hope (no ENSO differentiation) over the months of January through March has been increasing (optimal linear regression, $P < 0.05$) suggesting that more winter precipitation is going into river flow rather than accumulating as snow pack (Fig. 13). Though further analysis is required, this analysis does suggest that winters in the Fraser Watershed are warming and annual hydrographs are changing.

EN ROUTE MORTALITY ESTIMATES

In July, 1998, during the sockeye salmon fishing season, analyses provided by Fisheries and Oceans Canada staff indicated that high pre-spawning and/or en route mortality could be expected. This prediction was based on published relationships between run timing and Fraser River temperatures, and mortality observed in-river and on the spawning grounds in past years. In early August, the Department reported that the Early Stuart sockeye run had not arrived at their natal streams in expected numbers. These factors prompted Canada to request that the Fraser River Panel increase the gross escapement target for Summer-run

sockeye to ensure that adequate numbers of fish would escape through the commercial fisheries to offset expected losses. In mid-August, the Panel agreed to an increase to offset an expected 25% pre-spawning mortality (i.e., a 33% increase to the target). The revised gross escapement goal for Summer-run sockeye was exceeded, while nearly all the returning Early Stuart and a large fraction of the Early Summer sockeye escaped past Mission. Estimates of Late-run sockeye gross escapement at Mission were near or above the targets established by Canada.

The International Pacific Salmon Fisheries Commission (IPSFC) and the Pacific Salmon Commission (P.S.C.) have estimated sockeye salmon gross escapements by stock group via hydroacoustic monitoring at Mission each summer for 22 years from 1977 to 1998 (Banneheka et al. 1995). We compared the in-season escapements estimated at Mission to the sum of up-stream estimates of catch in aboriginal and recreational fisheries obtained by Fisheries and Oceans Canada and spawning escapements obtained by the IPSFC between 1977 and 1985, and by the Department between 1986 and 1998 (e.g. Schubert 1994). The analysis was done for each stock group and incorporated with in-season stock composition estimates from the analysis of scale samples and other biological data obtained from lower Fraser River test fishing catches. Data from four stock groups were tabulated and graphed: (1) Early Stuart, (2) Early Summer, (3) Summer runs, and (4) Late runs. Subsequent statistical analyses were performed after combining the two Summer groups because, historically, temporal overlap between the summer groups has made racial identification difficult and group differentiation is subject to annual uncertainty. The early Summer stock group is small compared to the Summer run and susceptible to estimation errors independent of other sources of discrepancies which frequently results in positive biases in Mission estimates. The rest of the stock groups are generally isolated in time, although in 1998 the early portion of the Late run overlapped with the Summer-run stocks in mid- to late August and early September. Final racial analyses have not been completed for past years and are, therefore, not available to this examination of 1998 differences between the estimates of gross escapement.

After the spawning ground information was compiled in late fall, it became evident that the upstream estimates (Table 3, i.e., in-river First Nations and recreational catch plus spawning escapement) for every stock group were lower than the numbers estimated in-season at Mission (Table 3, "in-season"). This discrepancy remained after subsequent reanalysis of stock composition data provided updated estimates of gross escapement at Mission (Table 3, "post-season").

Table 3. Estimates of en-route mortality of sockeye salmon in 1998 based on the differences between hydroacoustic estimates of escapement at Mission (plus First Nations catch below Mission) and in-river First Nations and recreational fishery catches and spawning escapement. (Post-season racial analyses have been applied to Mission and to catch estimates.)

<u>Stock Group</u>	<u>Mission In-season</u>	<u>Hydroacoustic Post-season¹</u>	<u>In-river Catch</u>	<u>Spawning Escapement</u>	<u>Mission^a-Upstream^b Discrepancy</u>
Early Stuart	167,800	183,800	15,300	31,000	137,500
Early Summer	598,600	567,200	58,900	227,700	280,600
Summer	4,125,400	4,512,100	542,700	2,383,500	1,585,900
Late	<u>3,624,400</u>	<u>3,312,100</u>	<u>139,900</u>	<u>1,782,400</u>	<u>1,389,800</u>
Totals	8,516,200	8,575,200	756,700	4,424,600	3,393,800

^a Post-season racial identification estimates applied to Mission hydroacoustic estimates (P.S.C.) *plus* First Nations fishery catches below Mission and Upper Pitt River escapement estimate (D.F.O.).

^b The sum of the in-river catch (aboriginal and recreational) and spawning escapement estimates (D.F.O.).

The discrepancies between Mission and upstream estimates of catch and escapement in 1998 were numerically the largest on record for Early Summer, Summer, and Late-run sockeye stock groups, and were the largest percentage discrepancies recorded for Early Stuart, Summer, and Late-run stock groups (Fig. 14). Even though the percent deviation for Early Stuart sockeye in 1998 was the highest on record, the largest negative numerical discrepancy for the Early Stuart stock group occurred on the large dominant return in 1997 (Macdonald and Williams 1998). Early Stuart returns in 1998 were low compared to previous years and, therefore, the absolute difference between Mission and upstream estimates was comparatively small.

Discrepancies in the estimates of the size of all stocks past Mission were negative and therefore could not be explained by errors in racial analysis which would produce discrepancies in both a positive and negative direction. One or a combination of four events can explain the source of the observed discrepancies in 1998. (1) Estimates at Mission were too high; (2) estimates from the spawning grounds were too low; (3) in-river fishing estimates were too low; and (4) en route losses of sockeye salmon occurred in the Fraser River. With the exception of our estimates from Mission, which have been confirmed most years since the mid-1990's with estimates from a similar facility at Qualark Creek (Enzenhofer and Cronkite 1998), it is difficult to provide independent confirmation or rejection of any of these possible explanations on an annual basis.

The reliability of estimates of in-river fishery mortality and spawning ground escapement are supported by a strong positive correlation between Mission estimates and spawning ground counts for each of the four stock groups since 1977 when data were first available (Fig. 15). We were unable to reject the null hypothesis that the relationship between the upstream and Mission gross escapement estimates approximates a 1:1 line ($H_0: b=1$, regression - $P<0.05$). Therefore, for two decades, Mission estimates of stock strength are largely accounted for in the in-river fisheries and the spawning ground estimates. During most years, the discrepancies between the stock size estimates fall within 95% confidence

intervals¹, on both sides of the equation, which suggests that up-stream estimates are unbiased and most natural and fishery-induced en route mortality can be explained within the natural variation associated with the estimation methods. However, during years when in-river migratory conditions were difficult (e.g. 1994, 1997, 1998), abundance of some stock groups could not be predicted by the historical relationship since they fell outside the 95% confidence intervals.

The discrepancies have a pattern in that there is heterogeneity among the residuals -- they are more likely to be larger during years in which run sizes are large (Fig. 16a, b, c). As run sizes have been increasing with time, many of the largest discrepancies have occurred in the 1990's. Furthermore, both Fraser River flows and temperatures during July, and temperatures alone during the rest of the summer, can account for additional patterns in discrepancy (regression of residual vs flow or temperatures – $P < 0.05$). The years when Fraser River flows are high in July in coincidence with the early Stuart run (e.g. 1997) are years which tend to have negative discrepancies. Conversely, discrepancies during low flow years are positive (Fig. 17a). Nineteen ninety-eight was a clear exception to this trend when extreme temperatures in the river caused a negative discrepancy in estimates of the early Stuart run. Had temperatures been lower, the small size of the Stuart run and low flow conditions would likely have led to a small discrepancy, possibly in a positive direction, rather than an en route loss of 137,000 fish (Table 3). Water temperatures, not flow, account for residual patterns in the summer and late runs (Fig. 17b, c). During cool years, discrepancies are positive but become negative as water temperature rises. We suspect that this temperature effect occurs when river temperature exceeded 17 or 18°C for prolonged periods such as 1994 and 1998 (and perhaps 1958 and 1961 where only empirical data exists). This relationship is stronger with the summer runs, where 22 years of data were available (regression analysis $P < 0.05$), than the late runs where $n=8$. We conclude that water temperatures were not benign in 1998 and were a source of problems for all stocks migrating through the Fraser watershed.

An alternative analysis was considered in which outlier data points that represent years of unusual migratory conditions (i.e. 1994 and 1997 Early Stuart data) were excluded because they are perhaps not representative of the historical relationship. A regression analysis with the modified database has narrower 95% confidence intervals and fewer stock group/year estimates fall within the predictive ability of the historical relationship. Inclusion of all historical data (1977-1998) is the most conservative approach and yet illustrates both the general reliability and limitations of our estimation methodology.

EARLY STUART

The in-season estimates of gross escapement at Mission and from upstream catch and spawning ground arrivals were similar prior to 1992. Upstream totals averaged 9.4% lower than Mission estimates as a result of either estimation error or residual en-route mortality, or a combination of the two. Between 1992 and 1998, six of seven years show lower upstream estimates than obtained at Mission. In this time period, two years had very warm river water temperature (1994 and 1998) and, in a third, the river discharge was extremely high (1997). During the peak upstream migration of Early Stuart sockeye in 1997, the high water velocities and turbidity stopped the migration of sockeye in the Fraser Canyon (Macdonald et al. 2000).

¹ A regression of Mission versus upstream was also performed (reversed x and y axes) to evaluate the potential for errors-in-variables effects. The slopes of the regressions were statistically indistinguishable and the 1998 data point fell outside the 95% confidence interval in both analyses.

Many of those fish present in the Canyon during this event did not complete their migration. The discrepancy between upstream estimates and Mission estimates were highest during these extreme years. All discrepancies were negative: 1994 - 64%; 1997 - 52%; and 1998 - 73%. Either hydroacoustic estimates of escapement are high in years of high temperature (which are, generally, low flow years – Table 1) and in years of high discharge (which tend to be low temperature years) or en route mortality can be severe in years of extreme environmental conditions in the river. Our regression equation (Fig. 15, 1977-1997) predicted an upstream Early Stuart catch and escapement in 1998 of 165,000 fish (95% C.I.: 0 to 474,000) given an in-season estimate of 168,000 fish at Mission. The difference between the number of fish estimated from the regression equation and the number of fish accounted for upstream (Table 3 - 46,000) is 119,000 fish; however, the observed estimate is within the 95% confidence interval for the prediction.

EARLY SUMMER

The Early Summer stock is comprised of a large number of small spawning populations that are subject to relatively large positive estimation errors at Mission as a result of stock identification errors (Fig. 15, $b < 1$, $P < 0.05$). Both 1997 and 1998 fall outside of the 95% C.I. as large negative discrepancies suggesting large losses as a result of severe migration conditions. The regression equation predicted a 1998 upstream escapement (catch + spawning escapement) of 480,000 sockeye (95% C.I.: 390,000 to 570,000). The estimated upstream escapement of 287,000 sockeye represents a deviation of -57% from the Mission hydroacoustic estimates (Table 3).

SUMMER

Comparison of Mission and upstream escapement estimates reveal negligible bias as shown in Fig. 15. Note the 1:1 line superimposes the best-fit regression line. The Mission and upstream gross escapement estimates for years prior to 1993 fit the 1:1 line well. Estimates for 1993, 1994 and, in particular, 1998, deviate from the 1:1 line. A linear regression of all years prior to 1998 predicts that an upstream total of 4,280,000 fish (95% C.I.: 3,760,000 to 4,800,000) would be expected from the gross escapement at Mission of 4,172,000 Summer-run sockeye. The observed upstream abundance was 2,926,000 fish, which was 1,586,000 fish less than estimated at Mission. The upstream value fell outside of the 95% confidence interval for the Mission estimate.

LATE RUN

Late-run sockeye salmon abundance has been estimated on Adams River/Lower Shuswap River dominant cycle years (1978, 1982, 1986, 1990, 1994, 1998) and in 1996 and 1997 (Fig. 15). While Late-run stocks exist in other years, numbers of fish are considerably lower. The presence of large numbers of pink salmon in odd-numbered years makes estimation of sockeye via hydroacoustic methods insufficiently precise to use for gross escapement estimation. The seven years of data that are available generally follow the 1:1 line (Fig. 15). Given the 1998 Mission estimate of 3,574,000 fish (Table 3), our regression equation estimates 3,505,000 will be recovered in upstream fisheries and on the spawning ground (95% C.I.: 2,324,000 to 4,686,000). The observed estimate of 1,922,000 fish was 1,752,000 less than estimated at Mission and would be outside the 95% confidence interval for the upstream estimate.

TOTAL SOCKEYE

Summing the four stock group estimates, the expected upstream total is 8,421,000 fish as calculated with the regression equations and Mission estimates of 8,575,000 fish during the fishing season. The estimated in-river catch and spawning escapement was 5,181,000 sockeye salmon (Table 3). This leaves a discrepancy of 3,394,000 fish, which is by far the largest shortfall since the introduction of the Mission facility. Percentage differences for the Early Stuart and Summer stock groups were the highest measured in the data sets.

PRE-SPAWNING MORTALITY (PSM) ESTIMATES IN FRASER SOCKEYE

The incidence of pre-spawning mortality among female sockeye salmon spawners is a potential index of stress during migration to spawning areas. Pre-spawning mortalities in Fraser River sockeye have been attributed to several causes: high water temperatures, difficult migration conditions (e.g. rock slides blocking passage), diseases of several types, and early annual migration timing for individual stocks (reviewed by Gilhousen 1990). However, past work has shown that these factors alone or in combinations account for only a small portion of the variability in the observed pre-spawning mortality rates (Gilhousen 1990).

PRE-SPAWNING MORTALITY - DATA

Pre-spawning mortalities are determined annually for each stock group by estimation of amount of eggs retained in carcasses during recovery and streamside enumeration activities on the spawning grounds. Females are scored by visual examination as unspawned (0-25% egg expulsion), partially spawned (25-75% expulsion), or completely spawned (75%-100% expulsion). For each stock the annual pre-spawning mortality rate (proportion of unspawned females) is determined by assuming that all of the fish in the unspawned category and 50% of the fish in the partially spawned category died before successful spawning. Data are presented for 1948-1998. These data were collected by the IPSFC until 1984 when the Department of Fisheries and Oceans took on this responsibility.

PRE-SPAWNING MORTALITY - OBSERVATIONS

The incidence of pre-spawning mortality across Fraser River sockeye stocks exhibits considerable yearly variation ranging from 0% to 84.6% during the period from 1948 to 1998. Horsefly sockeye salmon illustrate a dramatic case of this variability (Fig. 18). In 1998, pre-spawning mortality in seven of eight major sockeye stocks was at or below mean observed levels and well below maximum observed values (Table 4). Early Stuart sockeye were the exception to this pattern with the 1998 return having the highest pre-spawning mortality on record. Pre-spawning mortalities were also significantly correlated across several of these stocks (Table 5).

Table 4. Maximum and mean female pre-spawning mortality (PSM) rates on eight major spawning grounds in the Fraser River watershed. Fifty or fifty-one years of data are available. Stocks are shown in relative order of return with earliest return at the top of the table and latest at the bottom.

PSM: 1948-1997					
Spawning Ground	Maximum	Year	Mean	PSM 1998	No. of Years
Early Stuart	39.0%	1949	10.7%	44.0%	51
Horsefly	84.6%	1971	17.7%	13.9%	51
Stellako	44.0%	1963	9.9%	1.4%	51
Late Stuart	54.5%	1953	9.0%	1.7%	50
Chilko	61.7%	1963	9.0%	8.6%	51
Birkenhead	37.1%	1969	10.2%	4.6%	51
Adams	12.8%	1967	3.2%	4.3%	51
Weaver	51.6%	1996	7.9%	9.6%	51

Table 5. Pair-wise correlations of pre-spawning mortality rates between eight major Fraser River sockeye stocks using data from 1948 to 1998. An * indicates correlation coefficients that are significant at $p < 0.05$ level.

	Early Stuart	Horsefly	Stellako	Late Stuart	Chilko	Birkenhead	Adams	Weaver
Early Stuart	1							
Horsefly	0.19	1						
Stellako	0.25	0.13	1					
Late Stuart	0.25	0.19	0.41*	1				
Chilko	0.25	0.39*	0.52*	0.26	1			
Birkenhead	0.16	0.35*	0.57*	0.45*	0.69*	1		
Adams	0.06	0.06	0.26	0.23	0.06	0.17	1	
Weaver	0.05	-0.12	0.05	-0.04	-0.05	-0.09	0.26	1

In particular, summer run stocks (Horsefly, Chilko, Stellako and Late Stuart) and Birkenhead sockeye tended to be significantly correlated with each other. These stocks enter the Fraser River at similar times (Fig. 19) which suggests that a common factor(s) may be affecting pre-spawning mortality rates. However, a positive correlation between a number of populations that migrate through Hells Gate and the Birkenhead population that leaves the Fraser below Hells Gate suggests that part of the cause of common variation occurs before the fish reach Mission.

PRE-SPAWNING MORTALITY - POTENTIAL INDICATORS

Considerable work has been done to identify indicators that are useful for forecasting the occurrence of high pre-spawning mortality events and adjusting management strategies to compensate for potential losses in stock productivity. Gilhousen (1990) found that Fraser River temperatures during the migration and/or the peak time of the annual migration were significantly correlated to pre-spawning mortality rates for several stocks. We repeated Gilhousen's analysis of the relationship of peak run timing at Hells Gate and Hells Gate water temperatures to pre-spawning mortalities from 1974 to 1998 for the stocks in Table 6. We took advantage of data collected since the publication of the Gilhousen analyses and used only those data available since the construction of the Mission estimation facility.

Hells Gate Peak Run Timing. Peak run timing (e.g. 50% of the run recorded) for each stock was estimated from escapements past the Mission hydroacoustic facility and stock identification based on scale samples from test fisheries. Run timing at Hells Gate was assumed to be 4 days later than at Mission for all stocks, except for the Birkenhead and Weaver. For the Birkenhead and Weaver stocks, Mission run timing was used because of its proximity to their spawning grounds. The Mission hydroacoustic facility began operation in the mid-1970's, so run timing and the corresponding weighted Hells Gate temperatures before that time were not available for this analysis.

From 1974 to 1998, peak Early Stuart and Summer Run escapement past Hells Gate has been occurring at later dates (Regression, $P < 0.01$). Recently, Early Stuart sockeye salmon have been arriving an average of 2 weeks later than they did in 1974 (Fig. 20). Conversely, late summer stocks (Birkenhead, Adams, and Weaver) are unchanged or are arriving slightly earlier. In 1998, dates of peak migration past Hells Gate for the Early Stuart, Chilko and Birkenhead sockeye were near average while Horsefly, Stellako, Late Stuart, Adams and Weaver runs arrived 6-9 days later than the long term average from 1974 to 1997 (Table 6).

Table 6. Maximum and mean peak migration dates past Hells Gate for eight major Fraser River sockeye populations.

Hell's Gate Peak Run Timing (1974-1997)					
Spawning Ground	Earliest	Year	Mean	1998	Years of Data
Early Stuart	7-Jul	1975, 1978	12-Jul	13-Jul	24
Horsefly	2-Aug	1974	14-Aug	20-Aug	24
Stellako	3-Aug	1977	14-Aug	20-Aug	24
Late Stuart	3-Aug	1977	12-Aug	20-Aug	24
Chilko	5-Aug	1977	15-Aug	14-Aug	25
Birkenhead*	15-Aug	1980	26-Aug	27-Aug	25
Adams	30-Aug	1996	25-Sep	17-Sep	10
Weaver*	7-Sep	1996	24-Sep	15-Sep	16

*For Birkenhead and Weaver sockeye, peak run timing dates were at Mission.

Earlier arrival dates at Hell's Gate (or Mission for Birkenhead and Weaver) were associated with higher pre-spawning mortalities in all eight stocks. However, this relationship was only significant for the Chilko ($R^2 = 0.26$) and Late Summer run stocks ($R^2 > 0.32$), and was weak ($R^2 < 0.16$) for the Early Stuart, Horsefly, Stellako, and Late Stuart sockeye. On average across all eight stocks, each week earlier in peak arrival date was associated with a 4.7% (range 0.2% to 11.9 %) increase in pre-spawning mortality.

Hells Gate Temperature. Mean Hells Gate water temperature experienced by each stock was calculated by weighting daily water temperatures at Hells Gate during passage by the proportion of the run passing through Hells Gate on that day. For the Birkenhead and Weaver stocks, mean temperatures were calculated using daily escapement at Mission and water temperatures from Hells Gate, which are roughly the same as at Mission (M. Foreman, personal communication). In 1998, the weighted mean water temperature at Hell's Gate during migration set new record highs for seven of eight stocks and was the second highest on record for the Birkenhead (Table 7, Fig. 4).

Table 7. Maximum and mean Hells Gate water temperatures during migration for eight major Fraser River sockeye populations.

Mean Hells Gate Water Temperature (1974-1997)					
Spawning Ground	Max	Year Mean 1998			Years of Data
Early Stuart	17.3	1987	15.3	18.4	24
Horsefly	18.9	1981	16.9	19.1	24
Stellako	18.9	1994	16.9	19.1	24
Late Stuart	18.9	1994	17.0	19.1	24
Chilko	18.9	1981	16.8	19.4	25
Birkenhead*	18.7	1981	16.3	18.4	25
Adams	16.2	1996	13.9	16.6	10
Weaver*	16.0	1994	13.4	16.9	16

* For Birkenhead and Weaver sockeye, water temperatures are based on run passage at Mission.

Between 1974 and 1998, mean Hells Gate temperatures during migration have increased significantly ($P < 0.05$) for the Early Stuart, Adams, and Weaver stocks but were unchanged for the summer run group. For Early Stuart and Adams sockeye, temperatures explain significant amounts of the variation in pre-spawning mortality (Early Stuart, $R^2 = 0.25$; Adams, $R^2 = 0.42$; $P < 0.05$). However, the Early Stuart relationship is not significant ($R^2 = 0.07$) without the inclusion of the 1998 data point which represents an outlier in terms of highest temperature and highest pre-spawning mortality observed (Fig. 21). The Adams relationship should be interpreted with caution because it has only nine data points and may not be important given that pre-spawning mortality occurs infrequently in this stock ($< 10\%$). A 1-degree increase in water temperature at Hells Gate is associated with 4.2% and 1.2%

increases in pre-spawning mortality for the Early Stuart and Adams sockeye, respectively. Across the other six stocks, Hells Gate water temperatures were weak predictors ($R^2 < 0.12$) of pre-spawning mortality. On average across all eight stocks, each degree increase in water temperature at Hells Gate resulted in a 1.4% (range -0.9% to 4.2 %) increase in pre-spawning mortality.

GILHOUSEN ANALYSIS

The significance of multiple regression relationships for pre-spawning mortality rate and the combination of mean water temperatures and peak passage times past Hells Gate were re-evaluated with recent data, to test the strength of the relationships identified for several stocks by Gilhousen (1990). In Gilhousen's analysis, significant regression models were found for Early Stuart, Horsefly, Chilko, and Stellako stocks but not for Late Stuart or Birkenhead; (Adams and Weaver were not evaluated).

Using data from 1974 to 1998, the Early Stuart, Chilko, Birkenhead, Adams, and Weaver stocks produced significant regressions. Both the temperature and peak run timing coefficients were significant ($R^2 = 0.34$, $P < 0.05$) for the Early Stuart (% PSM = 0.05 H.G. Temp – 0.01 H.G. Peak Date – 0.44). However, the significance of the temperature coefficient depends on the 1998 data point. Only the timing coefficients were significant for the Chilko ($R^2 = 0.25$), Birkenhead ($R^2 = 0.31$), Adams ($R^2 = 0.69$) and Weaver ($R^2 = 0.69$) stocks. For these four stocks, each day earlier in peak arrival at Hell's Gate results, on average, in a 1% increase in pre-spawning mortality. Care should be taken in interpreting the Adams and Weaver data because only 10 data points were available for Adams sockeye and Weaver data may be influenced by the operation of the spawning channel in that system. Notably, the Horsefly data, with nine data points, produced the strongest relationship ($R^2 = 0.94$) in Gilhousen's analysis (1990), whereas in our analysis, the Horsefly relationship was weak ($R^2 = 0.14$) with 17 data points.

The inclusion of data collected since Gilhousen's analysis (1987 to 1998), and the exclusion of early years where timing information was collected by test fisheries (pre-Mission hydroacoustic information), has produced results that contradict those provided by Gilhousen (1990) and cast doubt as to the causes of pre-spawn mortality. For several stocks, we also included data missing from Gilhousen's analyses for the period 1974 to 1987. To further explore this apparent contradiction, we performed a second analysis including data that were collected before 1974 (appendix tables in Gilhousen 1990). Our conclusions remained the same except that temperature and run timing become significant factors in explaining pre-spawning mortality of the Horsefly run ($R^2 = 0.36$, $p < 0.01$). The significance of this relationship is largely due to the inclusion of data from 1961 where Horsefly sockeye returned early (6 August) and experienced high water temperatures (19°C) and had high pre-spawning mortality (62%). However, water temperatures and run timing were not available in Gilhousen's report for several other years pre-1974 that had high pre-spawning mortality. Presumably, run sizes were small and/or run timing information was lacking. The relative lack of data points at extreme conditions (e.g. high temperature) reinforces the importance of securing additional data, through reconstruction of events before 1974, for all of the major sockeye stocks.

RELATION OF PRE-SPAWNING MORTALITY TO POTENTIAL EN ROUTE MORTALITY

Gilhausen (1990) has suggested that years with high pre-spawning mortality rates are not necessarily years during which there are large en route losses. His analyses of PSM were run with and without years and stock groups that had experienced en route losses, and he concluded that years with high en route losses had little influence on the overall relationship between PSM and possible causal factor(s). Using more recent data, we also conclude that no clear connection exists between the two types of mortality (Table 8). An association exists between the two types of mortalities only with the early Stuart stock group, possibly because it is more susceptible to en route losses. This supports the contention that the migration conditions that are severe enough to cull the more susceptible members of the stock during migration will continue to act in a cumulative manner as fish reach the spawning ground. In 1998, migration route temperatures were sufficiently severe to expect physiological stress, disease, and mortality in the early Stuart and other stock groups (see other Sections of this document). As a result the early Stuart fish suffered high levels of en route and pre-spawn mortality. However, large en route losses apparently suffered by every other stock group in 1998 were not accompanied with particularly large pre-spawn losses. Implicit in this observation is that two or more causal factors, possibly acting independently at different locations, influence mortality of sockeye during the later portion of their lives. It is also possible that these causal factors act above tolerance thresholds that vary within and among sockeye populations. This is a difficult hypothesis to test and, if true, will be a difficult situation to predict. There may be many mechanisms promoting death before spawning, e.g., disease, temperature, hypoxia, energy exhaustion, and predation -- all can cause death at any location along the migration route.

Table 8. Pair-wise correlations of pre-spawning mortality rates for eight major Fraser River sockeye stocks and residuals from the regression of Mission escapement estimates vs. upstream escapement estimates using data from 1977 to 1998. An * indicates correlation coefficients that are significant ($p < 0.05$). Negative correlations indicate higher PSM in years when en route losses occurred.

Stock	Early Stuart Residual	Summer Run Residual	Late Run Residual
Early Stuart	-0.47*		
Horsefly		-0.03	
Stellako		0.06	
Late Stuart		0.10	
Chilko		-0.10	
Birkenhead			0.06
Adams			0.11
Weaver			0.19

SOCKEYE MIGRATION BEHAVIOUR

Daily escapement estimates were made with hydroacoustic equipment on the Fraser River at Qualark Creek, which is 95 km upstream from the echo sounding station at Mission, B.C. At this site, fish tend to be shore-oriented, which permits the estimation of their passage

using a fixed-location hydroacoustic system (Burwen et al. 1995; Enzenhofer et al. 1998). A track-mounted fish deflection weir immediately downstream from a split-beam transducer forces fish offshore to pass through the acoustic beam, where the probability of detection is greater (Enzenhofer and Cronkite 1998).

A review of fish passage between July 2 and August 31, 1998, and select periods in 1998, was done to detect changes in fish migration behaviour in response to (a) First Nations gillnet fisheries, (b) increases in river flow rate, and (c) increased water temperature. Fan plots were produced daily to show the cumulative total and passage location of fish within the water column for each 24-hr period. Days were identified by Julian date (JD). Each fan plot locates the transducer and a series of radiating 'aims' at declining angles to cover the area of fish passage. A solid vertical line at 3.7-m range from the transducer denotes the end of the fish deflection weir. Passage of individual fish, detected by the automated tracking algorithm of the hydroacoustic system, is shown as a mean range and vertical position within the acoustic beam.

FISH BEHAVIOUR RESPONSE TO A GILLNET FISHERY

Periodic gillnet fishery openings in the Fraser River are available to First Nations people. We reviewed fish response to several openings by the Sto:Lo and Yale people that occurred in close proximity to the Qualark Creek facility. We examined two openings that occurred between July 30 and August 2 and August 5 and 8, 1998, and a third that occurred between August 20 and 22, 1997. Daily fan plots show the location of fish passage for the day prior, during, and day after the fishing period (Fig. 22.).

The fishing period of July 30-August 2, 1998, is illustrated by JD 210, 212, and 215 (Fig. 22a). On JD 210, the day prior to the opening, fish passage was concentrated in all transducer aims and at a range of 3-6 m from the transducer. While the nets were in the water (JD 212) fish passage was concentrated towards the river bottom and at an increased range (from shore). Passage numbers dropped dramatically from an average of 1000 fish/hr to less than 200 fish/hr at the onset of the fishery. Once the fishery closed, JD 215, passage moved back towards the shore and became spread throughout all aims. The second opening, on August 5-8, 1998, caused a similar response (Fig. 22b, JD 216, 219 and 221). Fish passage became concentrated toward the river bottom at an increased range (JD 219). Passage rate dropped from a high of 8000 fish/hr to less than 1000 fish/hr immediately following the onset of the fishery.

The reaction of fish to a gillnet fishery was also observed during the 1997 sockeye migration. Fan plots JD 231, 233, and 235 show an opening held between August 20 and 22 (Fig. 22c). On the day prior to the opening (JD 231) fish were distributed throughout the water column at a range of 3.5-4 m from the transducer with 51% of the detected passage observed in the lower three transducer aims. During the fishery, 74.6% of the detected fish were in the bottom three aims and were further from the shore (JD 233). On the day following the closure of the fishery (JD 235), fish moved back towards shore and were evenly distributed throughout the water column. Clearly, in-river gillnet fisheries cause delays in migration and likely force fish into river locations that are sub-optimal migration habitats.

FISH RESPONSE TO CHANGES TO RIVER FLOW RATE

Lower Fraser River discharge during the 1998 migration period was near record low levels (Fig. 3). In the period between July 3rd and 13th, the river level increased by 7%, from 4,030 m³/s to 4,300 m³/s, followed by a steady drop. During the increase in flow the river became very turbid and had large amounts of floating debris. Before water levels rose, (JD 184, July 3) fish were concentrated throughout the water column with the heaviest passage occurring in the bottom six aims (Fig. 23a). As the flow rate increased, fish began to move towards the surface (JD192 and 194). As the river level dropped, fish passage spread throughout all aims (JD 198, July 17).

High turbidity also affected fish behaviour in mid-July, 1997, when the early Stuart sockeye salmon were in the lower river. During this period water discharge rate at Hope reached 9,000 m³/s and large amounts of debris and high turbidity were noted. Some fish were observed on the water surface inside the upstream portion of the fish detection weir. On the day that the discharge rate exceeded 9,000 m³/s, 86.5% of the total fish passage within the top three transducer aims (Fig. 23b, JD 195, July 14). Two weeks later (JD 213, August 1), the river level and turbidity had dropped and fish passage was evenly spread throughout the water column. During this day only 46% of the detected passage was in the top three transducer aims.

This behaviour may be an attempt to avoid larger suspended material and potentially higher concentrations of sediment near the bottom (Maidment 1992). However, this behaviour may come with the cost of exposure to higher flow rates that occur in the upper portion of the water column and a greater susceptibility to in-river fisheries during openings that occur on the rising limb of the hydrograph.

FISH BEHAVIOUR RESPONSE TO WATER TEMPERATURE

During the 1998 migration period, water temperature in the vicinity of the Qualark Creek facility, increased steadily from 19°C on July 22 to a high of 21.2°C on August 3 (Fig. 4). Fan plots of JD 205, 210, and 215 (Fig. 24a) show fish passage remaining concentrated throughout the water column with numbers decreasing towards the surface. A review of passage behaviour during this high water event did not reveal any reaction by the fish with the exception of a period of bottom orientation during a gillnet opening. Low and high water temperature periods were also examined during the migration period in 1996, a cooler year than 1998. Fish were spread throughout the water column during periods when temperatures were 15.2°C and 18.4°C (Fig. 24b; JD 202 and 213). We detected the same behaviour as occurred in the higher temperatures found in 1998, despite there being fewer transducer aims available in the 1996 migration period. Water temperature likely does not vary with depth, negating any behavioural advantage to altered location.

SOCKEYE CARCASS COUNTS

MISSION CARCASS COUNTS

Since 1990, salmon carcasses observed on the surface of the river near Mission have been counted and reported by the crew of the P.S.C. hydroacoustic vessel. These counts are opportunistic, that is, they only account for carcasses seen during daylight hours when the vessel is close enough to identify the species. The expectation is to observe only a very low proportion of the downstream drift of dead fish at Mission. Factors which could influence the proportion observed include: river width (435m at Mission facility), the proportion of dead fish that float, proximity of carcasses within visual sighting distance, proportion drifting during daytime, and water turbidity and its influence on ability to see dead fish. Prior to 1998, the annual number of carcasses that were observed varied from 90 to 949 fish. Taken as a percentage of the sockeye escapement at Mission from late June through September 10 each year, carcass counts averaged 0.0125% of the upstream migrations (range: 0.0036% to 0.0210%) (Table 9). In 1998, the count totalled 1,566 carcasses or 0.0254% of the escapement to September 10. Thus, the 1998 counts were numerically and percentage-wise the highest on record.

Table 9. Comparison of weekly Mission estimates of sockeye salmon passage with counts of drifting carcasses at Mission six days later.

MISSION DATES	MISSION ESTIMATE ^a	CARCASS COUNTS (+6D)	CARCASSES AS % OF MISSION
JUNE 26-JULY 16	169,000	14	0.0082%
JULY 17-23	107,500	25	0.0233%
JULY 24-30	346,200	120	0.0347%
JULY 31-AUG. 6	853,100	260	0.0305%
AUGUST 7-13	1,059,600	401	0.0378%
AUGUST 14-21	990,200	311	0.0314%
AUGUST 22-30	1,189,200	324	0.0272%
AUG. 31-SEPT. 8	514,300	89	0.0173%
TOTALS	5,229,200	1,544	0.0295%

^a Mission estimates reduced by the estimated migration of sockeye into tributaries and First Nations catch downstream of Qualark Creek.

The largest previous sockeye carcass drift was observed in 1997, when approximately 728,000 Early Stuart and Early Summer sockeye were estimated to have perished in the Fraser Canyon after being blocked by high river discharge and turbidity. The carcass count in 1998 was 1.65 times the 1997 count, the only year for which an estimate of en route mortality is available. Simple expansion of the 1997 estimates for the 1998 observations would indicate approximately 1.2 million fish died en route in 1998. These comparisons must be made with caution. En route mortality associated with the high water conditions in 1997 likely resulted in a different carcass drift pattern than in 1998, when water levels were much lower. High water conditions create fish concentrations and mortality at specific locations where migration blockages occur. In these conditions, our ability to monitor carcasses may be enhanced. However, visibility may be impaired by the turbid conditions associated with high water.

The daily carcass counts peaked approximately 6 to 8 days after sockeye peak escapement at Mission (Fig. 25). In past years similar lag times have been recorded, and it is reasonable to assume that 6 days is the average time required for a fish to swim past, die, and drift back to the Mission facility (Clarke et al. 1994). Analyses from past years suggest that in-river fisheries above Mission are a source of carcasses that also influences counts at Mission. Migration behaviour changes when gillnets are in the vicinity, in a manner that may expose the fish to stronger currents and harsher conditions (see Sockeye Migration Behaviour Section). Carcasses lost from the net (dropouts) or discarded once landed may add to the Mission estimates. In 1998, most fisheries coincided with peak sockeye abundance in the lower river making it difficult to separate the influence of fishing pressure from natural losses due to high temperatures (Fig. 25). The first few carcasses appeared shortly after a fishery near Mission (Table 1). During the period before the next fishery at the end of July, carcass counts were 0.0233% (July 17th-23rd) of the sockeye escapement estimated at Mission. Once the fisheries were opened, carcass counts increased appreciably suggesting that the cumulative influence of migration conditions and in-river fisheries were responsible for many of the en route losses in 1998. The largest number of carcasses occurred in coincidence (assuming a 6-day lag) with the warmest water temperatures at Hells Gate (Fig. 4; 20-21°C) on July 24th-30th and August 7th-13th (Table 9). Carcass counts dropped off somewhat in early September (counts relative to migration at Mission from August 31 to September 8 = 0.0173%). Hydroacoustic monitoring of the escapement ceased on September 21.

IN-SEASON OBSERVATIONS OF MIGRATION

During the summer, casual observations of the behaviour of migrating fish are provided from several sources. During years when migrating salmon are in distress, a great deal of attention is focussed on the river, and these observations can provide detailed and accurate collaboration with the scientific information being collected from the fish and their habitats (Macdonald et al. 2000 (in press)). In 1997, numerous reports described many distressed fish, behaving in an abnormal manner, in unusual locations. Most of these reports came from the lower river and confirmed large en-route losses to the early Stuart migrants. In 1998, fisheries officers, local residents, and scientific staff spent substantial effort monitoring river conditions and the behaviour of the migrating salmonids throughout the watershed. Despite this effort, much of which was focused on the lower river, there were almost no reports of large sockeye salmon die-off, migration blockages, or abnormal behaviour (Table 10, Appendix B). Through late July and August there were many reports of small numbers of moribund sockeye milling at tributary mouths or floating, rotting carcasses in back-eddies. The timing of these reports from throughout the watershed was consistent with a premature die-off of early Stuart fish. The largest numbers of distressed fish were estimated in the 100's in late August from Bridge River

and the Fraser Canyon. Most reports involved less than 100 fish. Compared to 1997 when 1000's of dead and dying fish were reported, reports from 1998 do not support our hypothesis that many millions of sockeye succumbed to en route losses associated with severe water temperatures.

Table 10. A review of in-season reports from Fisheries and Oceans Canada staff and local residents regarding carcass sightings and reports of abnormal behaviour. Most listed tributaries are non-natal habitats where spawning is unlikely to be successful.

Date	Location	No. of Fish	Comments
July 25	Stoner Ck.	Unk.	Moribund fish seen while operating fish wheel
Aug. 1	"	Unk.	Sockeye entering Stoner and Bednesti Cks.
Aug. 3	Chilliwack	50	Sport fishers report carcasses - 3 hours of obs. time
Aug. 4	Nechako	80	C+P boat patrol report fish in Bednesti Ck.
Aug. 4-6	Emery/Spuz	Unk.	Science staff at Qualark report sockeye holding in cks.
Aug. 7	Churn Ck.	Unk.	D.F.O., fish holding in Churn Crk, carcasses at Churn Crk.
"	Quesnel	'a few'	C+P report carcasses in mainstem.
"	Sawmill	20/km.	Helicopter from Hope to Sawmill reports carcasses
Aug. 8	Haney	147	C+P boat patrol Haney to Hope reports floating carcasses and "1000's" more on the bars. Chinook + sturgeon too.
"	Siska	'Large number'	D.F.O. staff report unusually large no. carcasses
Aug. 9	mid-Fraser	'Small number'	D.F.O. staff report carcasses. Not as bad as 1997.
Aug. 10	Qualark	'Many'	Science staff report increased bottom orientation.
Aug. 11	"	119	Science staff report 100 fish in Emery, 19 in Spuzzum Cks
Aug. 11	Mission	18 plus	C+P boat patrol to Jones Ck. reports floating carcasses
Aug. 12	Aggasiz	22	Helicopter to Emory Ck. Carcasses floating and stranded.
Aug. 13	Emory Ck.	24	D.F.O staff report 23 alive; 1 carcass in the Ck.. net marked and fungus, undeveloped gonads.
"	Yale Ck.	0	D.F.O. staff
"	Spuzzum	20-30	D.F.O. staff report fish alive at mouth, fungus, 4 carcasses,
"	Ruby Ck.	1	D.F.O. staff, vertebrae
"	Coquihalla	0	D.F.O staff
Aug. 17	Hope	100	Helicopter survey to Emory Ck, in-river fishery. carcasses
"	Qualark	1000	Science staff report milling fish at night. Familiar pattern
Sept. 3	Thompson	21	Helicopter survey reports carcasses at Shaw Springs.

Our observations allowed us to develop an appreciation for the temperature susceptibility of Fraser and Thompson river chinook salmon stocks in 1998. In past years, chinook pre-spawn mortality has been reported at several locations in small numbers (ten to a few hundred), although in some locations these numbers may have represented a significant portion of the population (M. Galesloot, B. Rosenberger, personal communication, Appendix C). In 1998, there were many reports of losses in the Thompson, upper Fraser, Nicola, and Bowron systems. In the South Thompson River an estimate of 12,000 chinook, or 25% of the population, was reported as pre-spawn loss. Histological analyses reported severe gill infestation. Low water levels as well as high water temperatures were cited as being responsible. The only other year with reports of large chinook loss was 1994, another warm year in the Fraser watershed (Figs. 4, 5, 6).

LIFE SPAN ANALYSIS

River temperatures experienced by migrating sockeye in 1998 were sufficiently high to suspect the occurrence of en route mortality in all stock groups. Run timing delays may be a precursor to en route losses with migrants decreasing travel speeds as a result of impaired physiological function, reduced swimming capabilities and speeds, and/or a need to hold in cool water refuges near tributary mouths.

We compared the run timing (median date when 50% of sockeye had migrated past the Mission acoustic facility) of Chilko, Horsefly, Stellako, and Early Stuart sockeye salmon stocks among years from 1984 to 1998, and from 1994 to 1998 for the Adams stock. The run timing of each of the stocks in 1998 did not appear anomalous (Fig. 26).

Transit times are also compared, defined as the number of day's travel between the median date past Mission and the median date of arrival at the spawning grounds. Median arrival on the Adams River and Horsefly spawning grounds were the dates on which 50% of marking for the mark-recapture studies were completed. The date of the median live count at Henry's Crossing (13 km downstream of Chilko Lake) is used as the arrival date for the Chilko stock. The dates on which 50% of the population was counted through the enumeration fences on Forfar, Gluskie, and Kynoch creeks were pooled to estimate arrival dates of the early Stuart stock. Similarly, the fence on the Stellako River was used to estimate median arrival dates for the Stellako River stocks. Transit times are presented for available years since 1994, except for Early Stuart stocks, for which data are presented from 1988. Transit times from Mission to the spawning grounds varied little among years. The Chilko and Stellako stocks showed the largest discrepancies from average, 4 days slower and 5 days faster for the Chilko and Stellako stocks, respectively.

OBSERVATIONS OF FISH CONDITION ON THE SPAWNING GROUND

Several mechanisms may cause a correlation between the length of time sockeye salmon survive on the spawning grounds to condition of the fish on arrival. For example, fish in poor condition may have depleted energy reserves and/or be more susceptible to disease. We use the time between the date of the median carcass recovery (carcasses recovered for mark-recapture population estimation) and the median arrival date on the spawning grounds as an index of 'spawning life span.' The spawning life span of the Adams (+2 days), Chilko (+1), Horsefly (0), and Stellako (+2) stocks was similar or a few days longer than the average from previous years (Fig. 26). However, early Stuart fish on the spawning grounds in 1998 lived 5 days shorter than the average since 1988.

Stressful migratory conditions may reduce a fish's ability to endure handling stress. We expect fish in poor condition to be more likely to require ventilation after release from the tagging procedure. These fish are also more likely to be recaptured in the seine net used to capture sockeye for marking, since healthy fish are expected to move rapidly upstream from the tagging area. Pre-spawn mortality as estimated from surveys of carcass egg retention are also used to estimate spawner condition. A pre-spawning retrospective is presented in the Pre-spawning Mortality Section.

The early Stuart sockeye salmon in both 1997 and 1998, years in which migration conditions were difficult, had shorter spawning life spans, required more ventilation after tagging, and suffered low spawning success (high PSM) (Fig. 26 and 27). These data support the contention that migration conditions for the early Stuart stock were poor in 1997 and 1998. It also points out the usefulness of spawning ground indicators as a method of estimating spawner condition. Based on these indicators, other stock groups were in better condition than the early Stuart group, although higher than average numbers of Horsefly spawners were recaptured immediately after tagging and their spawning success was slightly lower.

During marking, sockeye are examined for net marks. The fraction of a stock that is net marked represents an index of total fishing effort experienced by that stock (from both commercial and native sources). To test whether sockeye experienced especially high fishing pressure in 1998, we compare the net mark incidence of several stocks from 1987 to 1998. Net mark incidences in 1998 generally were lower or similar to that observed in recent years, and not unusual compared to any year since 1987 (Fig. 28).

DISEASE OBSERVATIONS DURING SPAWNING

HISTOLOGICAL OBSERVATIONS FROM THE SPAWNING GROUNDS IN 1998

Since 1994, there has been an attempt to assess incidence of disease in Fraser sockeye salmon by tagging crews at the spawning grounds. Estimates are made as an additional activity to mark-recapture studies if time permits and are therefore inconsistent. Visual estimates of gill lesions are not a reliable indicator of incidence of disease with some virulent diseases killing fish before gross pathology is evident (Pacha and Ordal 1967). In addition, there is evidence to suggest that some Fraser River sockeye salmon that are infected with *Flexibacter columnaris*, do not have lesions visible to the naked eye (Williams 1973). The fish that were categorized in 1998 (see Stress and Reproductive Parameter Section) as being in 'poor' condition during migration did not have higher incidence of infection than those in 'good' condition ($P > 0.05$ - ANOVA). We conclude that reporting of the incidence of lesions by fisheries staff on the spawning grounds is of limited value as a measure of disease occurrence.

Laboratory examination of gill, liver, kidney and head kidney samples from Horsefly sockeye salmon, in the later stages of their spawning migration in 1998, indicated normal levels of damage for salmon at this life cycle stage (M. Kent, Pacific Biological Station, personal communication). Fungus and lesions were noted on the heads and opercula of several of the fish. Some gill samples had bacterial infections, lesions, lamellar aneurysms, and had excreted mucus. Kidney and liver samples had fatty deposits and hemorrhagic areas; helminths and microsporidian cysts were also detected in some kidney samples. Samples from four fish that had reached the spawning grounds, and were lethargic and in particularly poor condition, showed glomerulo-nephritis caused by large numbers of myxosporeans (genus *Parvicapsula*). These fish also displayed large areas of necrosis in the hepatic parenchyma that may have been associated with the kidney damage.

HISTOLOGICAL OBSERVATIONS – A PERSPECTIVE

Sockeye salmon are likely to die as a direct result of exposure to temperatures in excess of 23°C due to acute thermal shock (Servizi and Jensen 1977). However, exposure to temperatures > 15°C can also result in premature death of feral sockeye (Colgrove and Wood 1966; Pacha 1963, 1964; Williams 1973; Wood 1965). These deaths can result from a stress-disease-death process. Stress can be positive as well as negative. However, for this exercise we use the term stress in the limited context defined by Brett (1958): "*a state produced by any environmental or other factor which extends the adaptive response of an animal beyond normal range, or which disturbs the normal functioning process to such an extent that in either case, the chances for survival are significantly reduced.*" Stress in feral salmon populations is a result of cumulative effects of exposure to less than optimum environmental conditions. Stressed sockeye mobilize corticosteroids, produced in the interrenal cells in the kidney, to aid the "fight or flight" process (Fagerlund 1967). Corticosteroids, while providing an immediate advantage, compromise the immune system (Anderson 1990). This elicits a disease process that, if not checked, impacts the fitness of stocks (Wedemeyer 1970). While the impacts are reported as mortalities for an entire population, this process is a cumulative and complex process affecting different segments of a population in different ways. For example, the severity of the impact and toxicity of *Flexibacter columnaris* epizootics are influenced by water temperature and fish density. The sum of all synecological factors in the environment must be considered to understand the sustaining or modifying influence of a disease to a particular host (Becker and Fujihara 1978).

The disease process begins in the ocean with different segments of a population experiencing different environments or responding to similar environments in different ways. Sockeye from the 1971 Chilko run were sampled from the ocean at Lummi Island (Fig. 2). The early segment had irritated gill tissue, increased hematocrits, and elevated cortisol levels when compared to the peak fish (Williams 1977). Similarly, sockeye from the 1973 Horsefly run sampled from the ocean near Tofino and Lummi Island indicated elevated cortisols in the early segment of the run compared to the peak at both locations ($p < 0.001$) (Williams et al. 1977). Co-migrating stocks also show differences in physiological parameters. Sockeye from the Late Stuart run sampled at the same time and location as the 1973 Horsefly fish did not have elevated cortisols in either the early or peak run segments (Williams et al. 1977). Thus, co-migrating stocks as well as different segments of the same stock enter the Fraser River exhibiting different levels of fitness. The ability of these fish to successfully spawn depends on cumulative environmental impacts and the fish's ability to respond to stress.

Many studies in both the Fraser River and the Columbia River (Washington State) have concluded that high temperatures were associated with significant premature death rates in salmon spawning populations (Amend 1970; Anacker 1956; Anderson and Conroy 1969; Bullock 1972; Fujihara 1971; Pacha 1961, 1963, 1964; Pacha and Ordal 1962; Rucker et al. 1953). The IPSFC became interested in fish diseases associated with high temperatures following very high pre-spawning mortality of Fraser River sockeye in the early 1960's. In 1963, Dr. Pacha, from the U.S.A., was hired to examine fish on the spawning beds of the Stellako River. He isolated the pathogen *Chondrococcus columnaris*, now named *Flexibacter columnaris*, from Stellako River sockeye and the following year from Chilko River sockeye (Pacha 1963, 1964). This began a series of studies between 1963 and 1986. Mr. Jim Wood, a fish pathologist working for Washington State Fish and Wildlife, isolated a variety of organisms including the bacterium *F. columnaris* and the parasite *Ichthyothirius* (Ich) from the

1965 Stellako run (Wood 1965). Dr. Colgrove, a veterinarian working for the IPSFC, set up field studies on the 1965 Horsefly run to examine the use of cool water temperatures to control the *F. columnaris* pathogen (Colgrove and Wood 1966). Investigations of the 1973 Horsefly run indicated the presence of *F. columnaris* but this organism did not appear to be associated with pre-spawn mortality. *Aeromonas liquefaciens* was also identified in 1973 as well as heavy concentrations of fusiform bacteria (Williams et al. 1977).

Water temperature is a key environmental factor in the disease process. Studies in the Columbia River indicate that *F. columnaris* is generally not detectable until temperatures approach 15°C (Fujihara et al. 1971). Mortality rates are positively correlated to temperature, but severity is determined by other factors such as virulence. One low virulence strain of *F. columnaris* caused disease only when fish were injured and temperatures were greater than 18°C. A high virulence strain can produce mortalities in apparently clean fish and may develop lesions at relatively low temperatures of 13-15°C, and rapid mortality with little or no gross pathology at high temperatures of 20°C. (Pacha and Ordal 1967, 1970).

It is important to understand that water temperature is but one of many factors that impact migrating and spawning adult salmon. *F. columnaris* has been detected in resident fish species in the lower Fraser River (Colgrove and Wood 1966). In the Columbia River, studies have established that resident fish function as reservoir hosts and transmit the pathogen to anadromous salmonids annually during their spawning migration. Fish ladders contributed by increasing the density of fish and therefore the lateral transmission of disease (Becker and Fujihara 1978). Therefore, migration timing and length of exposure to resident fish species and fish density play an important role in the development of disease in feral salmon populations.

STRESS AND REPRODUCTIVE PARAMETERS - A REVIEW OF THE 1998 DATA

During the 1998 season, we monitored and evaluated both stress and reproductive parameters in pre-spawning, spawning and post-spawning sockeye salmon of the Horsefly River stock (mid-summer run group). This group entered the Fraser River during the warmest period of the year (Fig. 4). During migration to the spawning grounds, temperatures were well in excess of 20°C (Fig. 7a, b). The Horsefly run has a history of pre-spawning mortality during years in which water temperatures are high along the migration route (Gilhousen 1990).

Fish were collected near the completion of their migration but before the commencement of spawning from the Horsefly River 2 km above Quesnel Lake between August 28th and 31st. These fish were divided into two groups based on a survey of their external physical condition (fungus, skin lesions, and lethargic behaviour). Spawning fish were collected nearly 50 km upstream from Quesnel Lake in the Black Creek area between August 31st and September 15th. The earliest arrivals to the spawning grounds (August 31st) were grouped according to external physical condition, but later arrivals (Sept. 3rd - 15th) were all in good condition. On September 3rd a collection of fish that had completed spawning was made.

Four stress parameters and three reproductive parameters were examined: (a) plasma cortisol, a primary indicator of stress, (b) plasma glucose and (c) plasma lactate, both of which are secondary indicators of stress, (d) interrenal nuclear diameters (IRND), reflecting exposure

to chronic stress, (e) plasma estradiol, which declines with approaching maturity, f) 17,20 progesterone, an indicator of final maturation in males and females, (g) testosterone, an indicator of maturation in both males and females, and (h) 11-ketotestosterone, the main sex steroid in males. The fish that were collected in August (28th - 31st, most in pre-spawn condition) were also subjected to a histological examination. The fish collected on September 3rd and 15th were artificially spawned, the eggs were contained in capsules and placed in the gravel of their natal stream. After 170 - 190 accumulated thermal units (ATU's - approx. 8 days) the fertilization success rate of eggs from both the 'early' and 'late' groups were evaluated, and in late February (440 - 640 ATU's) hatching rate was estimated.

STRESS PARAMETERS

While data are sparse, comparisons with other Fraser sockeye stocks from previous years suggests that Horsefly sockeye salmon were experiencing high levels of stress as they arrived on their spawning grounds in 1998. Interrenal nuclear diameters of migrating Horsefly fish (6.2-6.4 μ ; Fig. 29) indicate that these fish were exposed to chronic stressors during their up-river migration (Donaldson 1981). Diameters were nearly as large as those recorded from early Stuart sockeye in 1997 during difficult migration conditions in the lower Fraser River (6-4-7.2 μ ; Donaldson et al. 2000 (in press)).

In 1998, female Horsefly sockeye salmon had plasma cortisol levels that were in excess of 300 mg/ml regardless of reproductive stage; with higher levels (approx. 600 -1200 mg/ml) exhibited by spent fish or migrating fish in poor condition (Fig. 30). These levels reflect exposure to acute stress but may also be associated with fish that (a) have chronic infections of *Saprolegina*, (b) are suffering from other diseases (Donaldson 1981; Fagerlund et al. 1995) or (c) are a reflection of the presence of 17,20-dihydroxyprogesterone (17,20P) (Barry et al. 1995). Cortisol levels were generally higher than those in other migrating Fraser River sockeye stocks in previous years. In 1997 high levels were recorded at Hells Gate, where samples from female early Stuart sockeye salmon exceeded 400 ng/ml but resting levels were approximately 100 ng/ml as migration effort declined (e.g. early Stuart run - Stuart Lake) (Donaldson et al. 2000 (in press)). Male migrating Horsefly sockeye had lower cortisol levels than females (below 200 mg/ml during migration, $P < 0.05$ - ANOVA) which is consistent with the literature (McBride et al. 1986).

Most of the Horsefly salmon had plasma glucose values that were within the normal range for migrating salmonids (5 mmol/l, Fig. 30). However some of the fish in the poor condition category, and those that were spent, had levels above those recorded in 1997 for early Stuart sockeye stressed during severe migration conditions (Donaldson et al. 2000). Glycogen reserves are maintained in the liver and muscle until late in the migration when they are converted to glucose as a last source of energy for spawning (French et al. 1983). Migrating fish that had mobilized this energy source in 1998 were likely stressed during migration as they were not ready to spawn based on their 17,20P plasma concentrations (Mazeaud et al. 1977) (Fig. 31).

The levels of lactate in Horsefly salmon at all the reproductive stages we examined indicated that these fish had been involved in severe exercise (Burgetz et al. 1998) (Fig. 30). Levels among healthy fish were highest during migration and declined during spawning. In 1997, sockeye migrating through the lower Fraser River had their highest concentrations of plasma lactate immediately after they had negotiated the Hells Gate fishway (Donaldson et al.

2000). However, 1997 values were still lower than the lactate values recorded in this study. Lactate is also a secondary stress factor, expected to be higher in fish in poor condition ($P < 0.05$ – ANOVA), and was likely a reflection of high water temperatures throughout the Fraser watershed in 1998.

A statistical comparison between fish categorized as being in 'good' or 'poor' condition during their migration to the spawning beds indicated that external appearance was not a good predictor of stress levels, reproductive impairment, or histological condition ($P > 0.05$ – MANOVA) (Fig. 29, 30, 31). When spawning fish were incorporated into the analysis the prediction improved, with high lactate levels showing some association with poor external appearance ($P < 0.05$). Female sockeye salmon were more likely to have higher stress levels (particularly cortisol) and testosterone ($P < 0.05$ – MANOVA) than males during the later migration period. After spawning, plasma cortisol, glucose, and lactate levels rose relative to most of the spawning fish, and plasma cortisol and glucose were higher than in many of the migrating fish as well. These discrepancies were largest when compared to migrating and spawning females in good condition (Fig. 30).

REPRODUCTIVE PARAMETERS AND SPAWNING SUCCESS

Reproductive parameters measured in the Horsefly females follow a pattern predictable in salmonids. Estradiol levels were high in the migrating fish in association with the process of vitellogenesis and oocyte growth, but declined on the spawning ground with the increase of 17,20P, final maturation, and spawning (Fig. 31) (pinks - Dye et al. 1986; sockeye - Truscott et al. 1986). Early Stuart sockeye salmon exhibited a similar hormonal pattern as they approached their spawning grounds in previous years (Donaldson et al. 2000 (unpublished manuscript); Donaldson et al. 2000). It is also common for females to exhibit higher plasma 17,20P concentrations than males (Fig. 31). However, there were several indications that the early portion of the 1998 Horsefly run was suffering maturation impairment. Many of the females, particularly those in poor condition, had low estradiol and progesterone levels, possibly as a result of a high temperature stress related suppression of estrogen synthesis and an inability to switch to the synthesis of 17,20P. These processes are known to be linked (Afonso et al. 1999). Stress associated with gillnet capture was shown to suppress estradiol synthesis and consequently vitellogenin levels during the Fraser River migration in 1993 (Donaldson et al. 2000 (unpublished manuscript)). Testosterone was also depressed in females in poor condition, further evidence that these fish will probably not reach maturity and will not spawn viable eggs (Fig. 31).

The optimum and upper threshold temperatures for sexual maturation of sockeye salmon have not been well defined. [It is known to be lower than those for swimming performance and osmoregulation.] While migratory sockeye frequently encounter temperatures of above 15°C during their upstream migration, they usually seek temperatures of 10°C in lakes and approximately 12°C in spawning streams. Elevated but sublethal temperatures are known to negatively affect secretion of the hormones controlling sexual maturation in sockeye salmon in the Fraser River. In an unpublished 1995 study, Dr. Craig Clarke exposed early Stuart sockeye salmon ($n = 40$) captured at Hells Gate, to two temperature treatments (15°C and 19°C) for 2 weeks at the Pacific Biological Station in Nanaimo, B.C. Two weeks of exposure to a temperature of 19°C in the laboratory reduced plasma testosterone levels significantly in both sexes compared with 15°C ($P < 0.05$). There was no significant interaction between the effects of temperature and gender (Fig. 32). Levels of 11-ketotestosterone and estradiol were low and below the detection limit in many fish at

19°C. Furthermore, circulating levels of the major hormones controlling sexual maturation were also depressed at 19°C. This is consistent with the finding of Manning and Kime (1985) that steroid biosynthesis was suppressed in rainbow trout testes at 17°C.

Reproductive impairment and reduced gamete quality and survival of progeny have been shown to result from a variety of stressors (Donaldson et al. 2000; Campbell et al. 1992, 1994). Clearly, the potential for suppression of sexual development and intergenerational impairment existed in the Fraser River in 1998 during the summer migration when temperatures exceeded 19°C at many locations and times. This possibility was given some experimental credence based on an assessment of the spawning success of the early Stuart and Horsefly sockeye stocks. Fertilization success was lower in 1998 than in 1997 in a comparison of several early Stuart spawning sites (Fig. 33a) (Herunter et al. 2000). Horsefly fish that arrived on the spawning grounds early in 1998 suffered even lower fertilization success rates than the Stuart fish, and only 10% of their eggs hatched (Fig. 33b). Egg hatching success (but not fertilization success) was influenced by the condition of the spawning female as estimated by stress and reproductive parameters ($P < 0.05$ – multiple regression). Females that arrived late tended to have lower levels of testosterone and spawned eggs that hatched more successfully (Fig. 31). These late arrivals likely experienced less severe water temperatures during their entire migration than early fish. The likely difference at Hells Gate was 18-19°C vs. 21-22°C (Fig. 4). These observations suggest that the upper threshold temperature for successful migration lies between 18°C and 22°C.

Comparisons with the 1997 spawning runs must be made with caution as both 1997 and 1998 were poor years for migration (extremely high water levels and extremely high temperatures, respectively) and as a result, no reference data exists. In addition, stress levels at the beginning of the spawning migration during the development and maturation of the eggs were not recorded in 1998. These parameters (stress and reproduction) must be recorded in both males and females throughout the migration in a number of years in order to understand the intergenerational influence of water temperature and discharge.

STRESS AND REPRODUCTIVE PARAMETERS - A PHYSIOLOGICAL PERSPECTIVE

Based on our general knowledge of fish physiology and the specific experiments reported above, a number of predictions can be made as to how the upstream migration of sockeye salmon in the Fraser River might have been adversely affected by the high water discharge and high temperature events experienced in recent years. We consider the validity of these predictions (phrased as questions, below), based on the available environmental and fisheries knowledge from the 1998 season that is presented in other parts of this document.

WAS THE UPPER INCIPIENT LETHAL TEMPERATURE LIMIT EXCEEDED?

Fish have a characteristic threshold temperature beyond which they die. The upper incipient lethal temperature is a statistically derived parameter predicting the temperature at which 50% of a fish population would die in a given exposure time. The exposure time used in the calculation is considerably shorter than the time required for most sockeye runs to negotiate their migration routes through the Fraser system. The upper incipient lethal temperature for young sockeye salmon is approximately 25°C (Brett 1952; Servizi and Jensen 1977). Given that water temperatures exceeded 22°C for at least a week in the Horsefly,

Nechako, and Stuart rivers during 1998 (Fig. 7a, 7b and 8) and their exposure time at these warm temperatures was several days (or even weeks), a proportion of sockeye salmon should have been expected to die.

WAS SWIMMING PERFORMANCE IMPAIRED BY HIGH WATER DISCHARGE - THE INFLUENCE OF BODY SIZE, DISEASE, AND STRESS?

All fish have a maximum swimming speed and duration level. Therefore, it is possible that as a result of high river discharge, water velocities in certain sections of the Fraser River can be above the upper swimming threshold of certain fish. A Fraser River discharge exceeding 8,000 m³/sec (measured near Hope) is thought to create passage problems for migrating sockeye (Macdonald and Williams 1998). At no time in 1998 did river discharge approach this level, and it was below 4,300 m³/sec for the entire period that sockeye were migrating to their spawning grounds (Fig. 3). However, certain categories of fish are predicted to be poorer swimmers than average as influenced by fish size, presence of disease, and stress. Any environmental situation that promotes a disproportionately larger number of fish in these categories could impair successful passage through hydraulic barriers.

Absolute swimming speed of salmon is directly related to body length (Beamish 1978). Consequently, small salmon have a lower maximum absolute swimming speed than large salmon. High water discharge could in theory favour the larger, faster fish. This appears to have been the case in 1997 for the Early Stuart run that was faced with a high water discharge (Macdonald et al. 2000). Males may also be better able to stem high water velocities than females because they have better swimming ability (Farrell and Tierney, personal communication). A disproportionately large percentage of male sockeye successfully reached the spawning grounds in 1997. The required analyses to test these ideas were not performed for 1998, but it is unlikely that water velocities were large enough to be a factor involved in en route losses.

En route and pre-spawn losses to Fraser and Columbia river sockeye have been attributed to bacterial infections that often cannot be diagnosed from external examination (reviewed in the Disease Observations During Spawning Section). Disease has been shown to adversely affect the critical swimming performance of mature sockeye salmon caught in Port Alberni Inlet and transferred to Simon Fraser University for swimming tests at 19-21°C, using a Brett-type respirometer (Jain et al. 1998). Critical swimming performance was reduced to 65% of normal by diseases, which included fungal infections. Initially, these diseases were not diagnosed, but were responsive to prophylactic treatment with chloramine-T and probably arose as a result of skin damage during transportation. In-river gillnet damage to the skin and high temperature in 1998 could have promoted similar diseases and performance reduction. However, both field and laboratory observations were unable to quantify the level of disease outbreak in 1998. Consequently, we can only speculate that severe conditions in the Fraser River and the high level of diseased fish observed in 1998 (see above) could have caused poor upstream migration success.

Stress can adversely affect swimming performance (Beamish 1978). Stress is assessed using endocrine variables (e.g., plasma cortisol), metabolic variables (e.g., plasma lactate), and behavioural variables. Based on elevated cortisol and plasma lactate levels, some of the fish from the summer stock group in 1998 were experiencing severe stress (see previous section). High plasma lactate levels are known to negatively affect swimming performance in sockeye salmon (Farrell et al. 1998) and rainbow trout (Farrell, unpublished

data). While the cause of these metabolic disturbances is unclear, muscle telemetry studies of sockeye salmon near Hells Gate in 1995 and 1996 suggest an important behavioural difference for fish that successfully negotiated Hells Gate (Hinch and Bratty 2000). Fish that successfully negotiated Hells Gate were characterized by a significantly slower approach speed and shorter residency time in the approach. Also, they never swam at speeds greater than their estimated critical swimming speed for longer than 3 minutes, whereas the unsuccessful migrants exhibited one or more periods of >10 min. Thus, a fish with an unsteady, frantic behaviour pattern is likely stressed, and appears less likely to successfully negotiate Hells Gate. Collectively, these studies suggest that the elevated stress observed in 1998 could produce en route losses because fish failed to negotiate hydraulic obstacles and were washed downstream as observed with the telemetry studies.

WAS THERE A FAILURE OF OSMOREGULATION?

Intense exercise may disturb osmoregulatory equilibrium. Rainbow trout forced to swim in the laboratory have a negative sodium balance (Wood and Randall 1973) and gain water. Thus, it might be expected that sockeye migrating through the Fraser Canyon would experience osmoregulatory distress at temperatures above average, but the available evidence does not support this conclusion. Sockeye captured at Hells Gate fishway in 1993, at 17°C, had plasma chloride values of 126 mEqL⁻¹, virtually identical to the level of 127 mEqL⁻¹ found in fish held in the laboratory (Kreiberg and Blackburn 1994). Similar studies have not been performed on sockeye salmon at the temperatures experienced in 1998.

WAS SWIMMING PERFORMANCE IMPAIRED BY HIGH TEMPERATURE?

Temperature has a profound effect on swimming ability. Brett (1971, 1995) clearly showed in laboratory experiments that sockeye salmon have an optimal temperature of around 15-18°C for critical swimming performance. At 20°C maximum swimming performance declined, while routine metabolism continued to increase with temperature. Because maximum cardiac performance shows a similar temperature profile and maximum cardiac activity is required for critical swimming in salmon (Farrell and Jones 1992; Farrell (1997)) suggested that the temperature threshold for maximum cardiac activity sets the temperature threshold for critical swimming performance in salmon. Subsequent field studies with Fraser River sockeye clearly confirm a temperature optimum of 17°C for swimming endurance, with almost a 20% reduction in swimming speed (total body lengths travelled) at 21°C (Fig. 34). A high water discharge would compound this effect. Given that water temperatures at Hell's Gate during the summer of 1998 were >18°C for 60 days (Fig. 5 b) and temperatures further upstream were >22°C (Fig. 7a, 8), maximum swimming performance would have been adversely affected in 1998. However, water discharge levels were near record low levels in 1998 (Fig. 3). It is unlikely that high temperature and high water discharge had compounding effects in 1998.

WAS RECOVERY FROM FATIGUE AND STRESS IMPAIRED BY HIGH TEMPERATURE - THE INFLUENCE OF GILLNETS AND DENSITY?

Salmon perform a series of intense bouts of activity during their migration that may result in fatigue from which they must recover. Full metabolic recovery after extreme exhaustion takes 12-24 hours (Milligan 1996). However, critical swimming performance of mature Port Alberni sockeye salmon at 19-20°C can be repeated with as short as a 40-min

recovery interval, and when metabolic recovery is far from completed (Farrell et al. 1998; Jain et al. 1998). Even at 21°C, following a simulated 1-h gillnet entanglement, a 3-h recovery period was sufficient for stress to subside sufficiently for endurance swimming performance of Fraser River sockeye salmon to be restored (Fig. 34, 35). These observations attest to the remarkable athletic prowess of the sockeye salmon, and suggest that the high water temperature did not adversely affect recovery from fatigue under good water quality conditions in 1998.

When faced with hydraulic barriers, salmon congregate to recover and prepare in holding areas above and below the barrier. If fish density is high compared with the size of the holding area, cumulative respiration could create local hypoxia. The likelihood of local hypoxia increases at high temperature when the oxygen solubility in water is reduced. Whether or not such situations exist is unknown, but further study is warranted. High fish densities in holding areas below hydraulic barriers are predicted to impair the fish's recovery from previous exhaustive exercise under conditions of warm temperature. In laboratory studies, the recovery of Port Alberni sockeye from a critical swimming test was impaired when the recovery took place in moderately hypoxic (100 torr), warm (19-20°C) water (Farrell et al. 1998). Only 20% of fish could perform a second swim challenge in normoxic warm water, whereas 100% of fish performed the second swim challenge when the recovery was in normoxic warm water. This effect of hypoxic water contrasts with the apparent tolerance (and perhaps a maladaptive behavioural preference) by sockeye salmon to severely hypoxic, cold, saline water while slowly moving up the Alberni Inlet at depth (Birtwell et al. 1997).

DID HIGH TEMPERATURE OR HYPOXIA IMPAIR SEXUAL MATURATION?

Sexual maturation is driven in part by elevated levels of sex hormones during the in-river migration. However, there is a threshold temperature above which hormone production is reduced. For rainbow trout testes the threshold is 17°C (Manning and Kime 1985). Based on the 1995 experiments performed by W.C. Clarke (see previous section), the threshold appears to be between 15°C and 19°C for Fraser River sockeye. Hypoxic conditions are more likely as temperature increases and may cause blood flow constrictions to visceral areas during hypoxia, and thus impair gonad maturation (A.P. Farrell, personal communication). Given the high water temperatures in 1998 both en-route and on the spawning grounds (Figs. 4, 7-9, 11), we predicted that plasma levels of the major sex hormones would have been depressed in Fraser sockeye salmon. This appeared to be the case for the Horsefly fish (see previous section, Fig. 31). The likely physiological consequences of these reduced hormone levels would be poor spawning success, poor egg quality and viability, and senescent death prior to spawning. There were indications of all three of these reproductive impairment problems in 1998 in each of the stock groups.

DID METABOLIC ENERGY STORES DEPLETION PREVENT UPSTREAM MIGRATION?

Salmon enter the river with a finite amount of energy stores (lipid, carbohydrate, and protein), and operate on a negative energy balance because they do not feed during their upstream migration. Metabolic energy stores could fall below the threshold for successful migration if (a) the initial levels were reduced, (b) the rate of utilization was increased, and/or (c) migration took longer than normal. There was no evidence that migration of sockeye salmon took longer than normal in 1998 (Fig. 26). The metabolic stores of fish entering the Fraser River were not measured in 1998. However, scientists at the Pacific Biological Station

(Fisheries and Oceans Canada) believe that the area in the N.E. Pacific Ocean for optimal survival of sockeye salmon has been declining during the past 2 decades. This has resulted in increased competition for resources and a reduction in the mean size of fish returning to the Fraser River (McKinnell 1997; Macdonald and Williams 1998). In 1997, as a result of high water velocity, some sockeye salmon depleted their lipid stores more quickly than in previous years. Consequently, muscle protein and glycogen reserves were utilized earlier in the migration than was expected under normal conditions; many failed to reach the spawning grounds (Donaldson et al. 2000; Higgs et al. 2000).

The elevated water temperature in 1998 would have increased routine metabolic rate. Given that water temperature in 1998 exceeded the average by 2-4°C (Fig. 6), it is expected that metabolic stores would have been reduced at least 25% faster during river migration. Avoidance of and recovery from encounters with in-river fishing gear would also decrease metabolic stores at a faster rate, as would encounters with high water discharge, exposure to hypoxic water, and the effort to counteract disease.

The timing of peak sockeye migration in recent years is 2 weeks later than in 1974 (Blackbourn 1987). Such a delay could draw down metabolic energy stores. However, if fish were holding in cold ocean waters, this negative impact could be minimized. Furthermore, delayed timing of the earlier runs (early Stuart and early summers) could move peak migration to a date beyond that of the peak in average river discharge (Fig. 3). A 10-day to 2-week delay in 1998 would have resulted in fish encountering on average a 20% lower water discharge. Given that the cost of swimming is a power function of velocity, energy savings from a delayed migration could be significant. If this migration delay is progressive over many generations, it is possible that it has been influenced by selective factors within the environment.

CONCLUSIONS

There are a number of compelling reasons to believe that severe migration conditions caused the very large en route losses that were seen during the 1998 sockeye season. High water temperature records were being established throughout the Fraser Basin and water levels were near record lows. Past experience has indicated a plethora of hazards face migrating sockeye exposed to these conditions. Migration blockages, susceptibility to diseases, impaired maturation processes, increases to stress parameters, reduced efficiency of energy use, and reduced swimming performance are all factors that become more hazardous as temperatures exceed 17°C. The early Stuart group, having further to swim than all other stocks and being in the river during the period when temperature deviations from normal were greatest (Fig. 6), quite likely succumbed in large numbers en route. There is much support for this conclusion: (a) en route losses were accompanied with large pre-spawn losses on the spawning grounds, an indication that similar mechanisms influenced both types of mortality (Table 4); (b) according to our residual analysis, if temperatures were benign, the small size of the Stuart run and the low flow conditions would likely have led to a much smaller discrepancy, probably in a positive rather than in a negative direction (Fig. 17a); (c) record numbers of carcasses were observed at Mission in late July-early August, the same period that carcass observations recorded from the rest of the watershed were highest (although in-river fisheries confounded the cause) (Tables 9 and 10); (d) fish condition and life span of Stuart fish, upon arrival at the spawning grounds, were particularly poor (Fig. 26, 27); and (e) stress

and reproductive parameters were not measured for Stuart fish, but other 1998 runs (e.g. Horsefly) were distressed (Fig. 29, 30, 31). We have reviewed the many types of physiological impairment that may result from the extreme temperatures that were recorded in the Fraser Basin during the summer of 1998.

An explanation of the en-route losses suffered by later run groups present a more complicated problem. Temperatures remained at record setting levels through late July, August, and September, yet deviation from long-term mean temperatures declined substantially (Fig. 6). In-river fishery discards complicated carcass counts at Mission (Fig. 25) and there were fewer reports of abnormal behaviour and mortality from up-river locations as the summer proceeded. Pre-spawn mortality was below in-season expectation (and below average, Table 4) for all but the Stuart stock, forcing us to consider the possibility that no clear connection exists between en route and PSM (Table 8). It is apparent that a complicated group of interacting factors influence both types of mortality, and existing modelling approaches are not adequate to provide accurate or even useful predictions. While stress and reproductive parameters indicated large numbers of distressed migrants, impaired sexual maturation, and possible intergenerational effects during the early portion of the Horsefly run, histological samples were normal, and other estimates of fish condition on almost all of the spawning grounds indicated condition was generally good (Fig. 26, 27). Finally, there is evidence to suggest that our run-size estimation capabilities decline as the runs increase in size (Fig. 16a, b, c). Heterogeneity of variance is not unusual in biological data sets; with the summer and late runs of 1998, it likely explains a portion of the estimated discrepancy (Fig. 15). Historically, extreme flow and temperature have also influenced the pattern of discrepancy (Figs. 17a, b, c) and were also responsible for some en-route loss in all stock groups in 1998. Ultimately, our ability to inventory our resource is not only fundamental to its management, but is also necessary if we are to better understand the causal factor(s) responsible for pre-spawn and enroute mortality.

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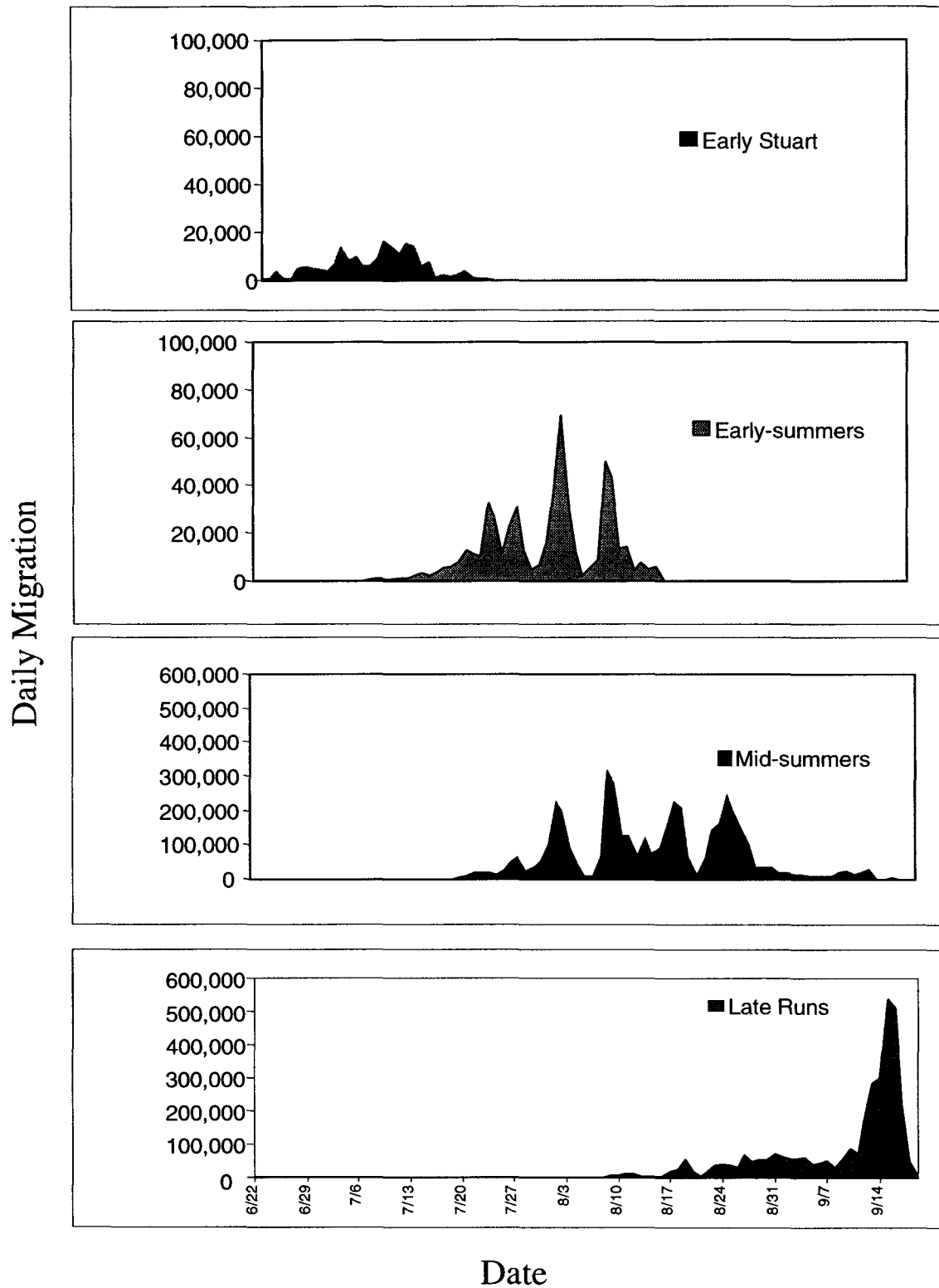


Fig. 1. Sockeye salmon daily run timing past the Mission hydroacoustic facility during the 1998 spawning migration. Four run groups are listed. Note that the Summer and Late stock groups were the largest runs in 1998 and have different y-axis scales.

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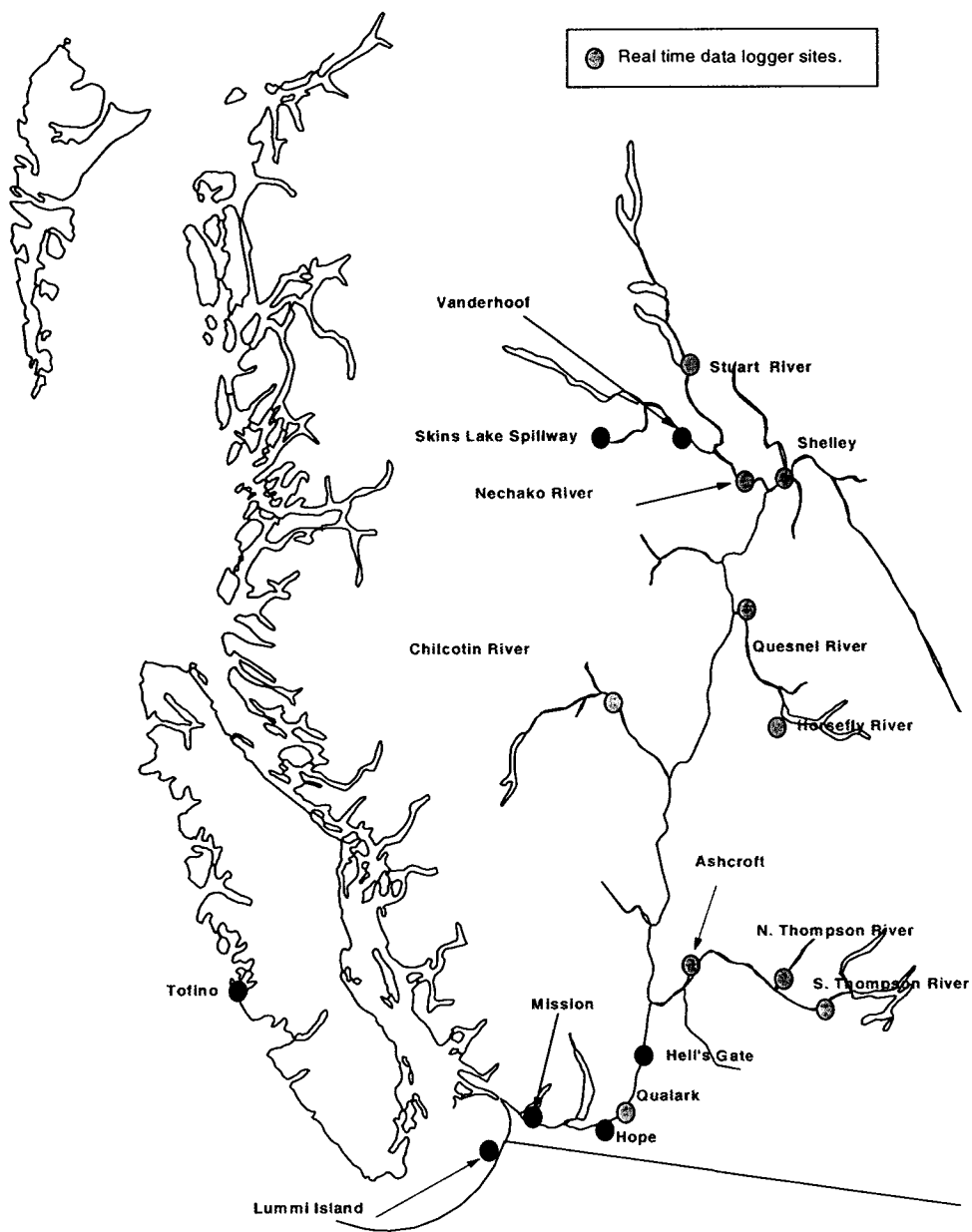


Fig. 2. The Fraser River watershed showing locations where water temperature and discharge acquisition equipment is installed. Geographical locations that are referred to in the text are also indicated.

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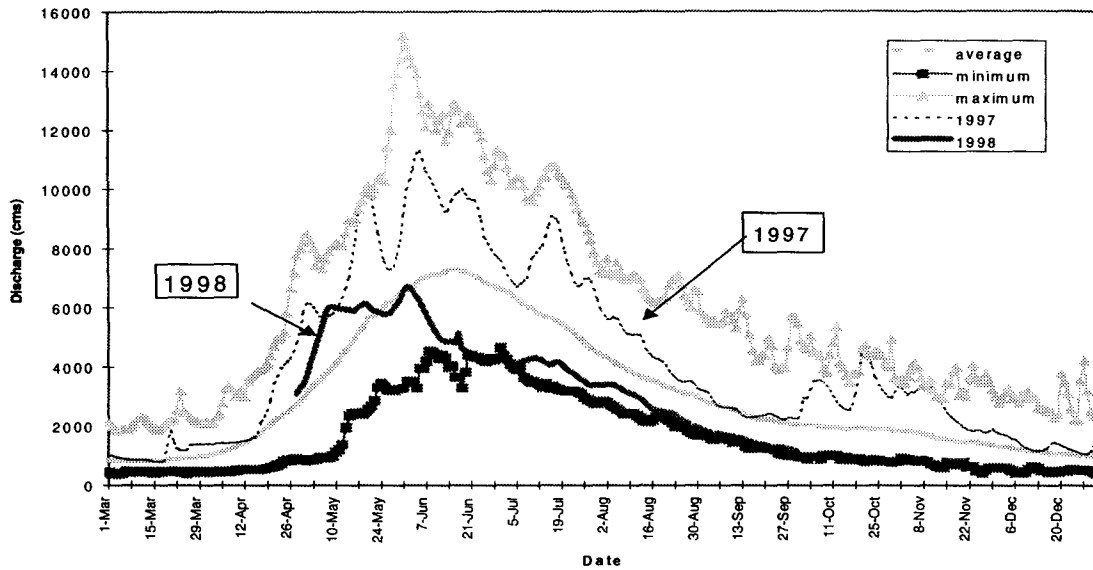


Fig. 3. Average Fraser River discharge at Hope since 1912, with daily discharge for selected high and low water years.

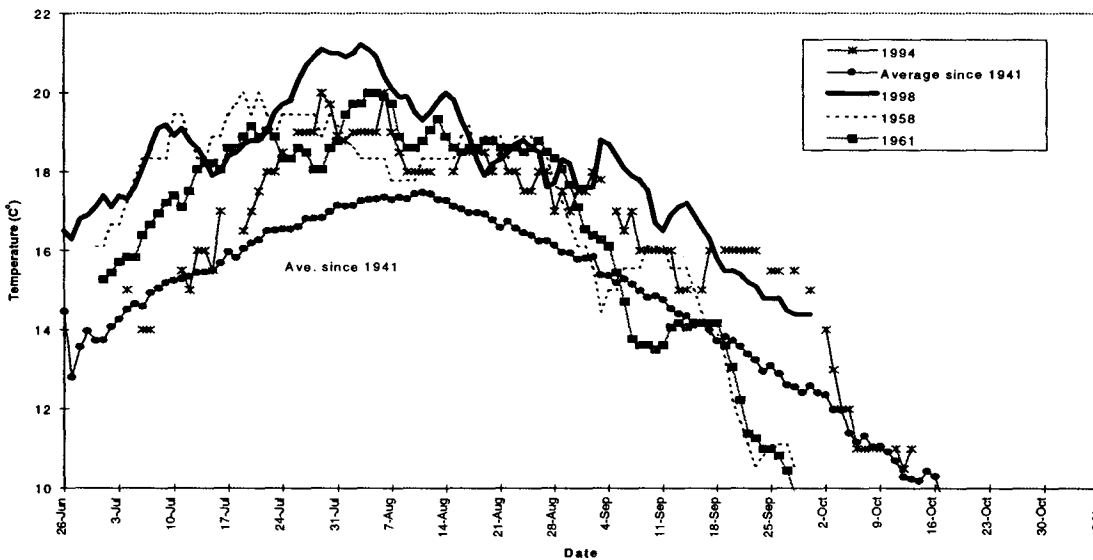
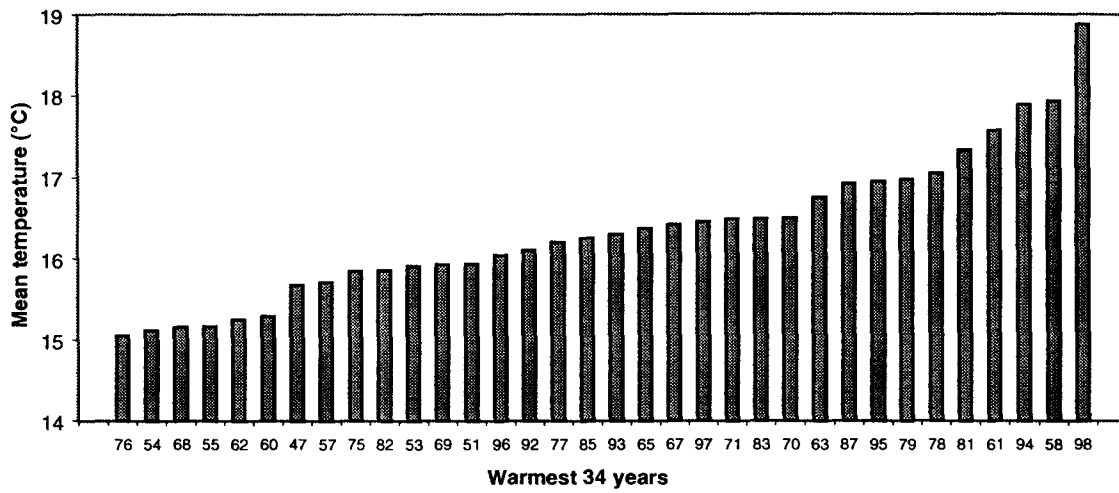


Fig. 4. Mean daily water temperature at Hells Gate since 1941 with daily temperature for 1998 and other warm water years.

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a).



b).

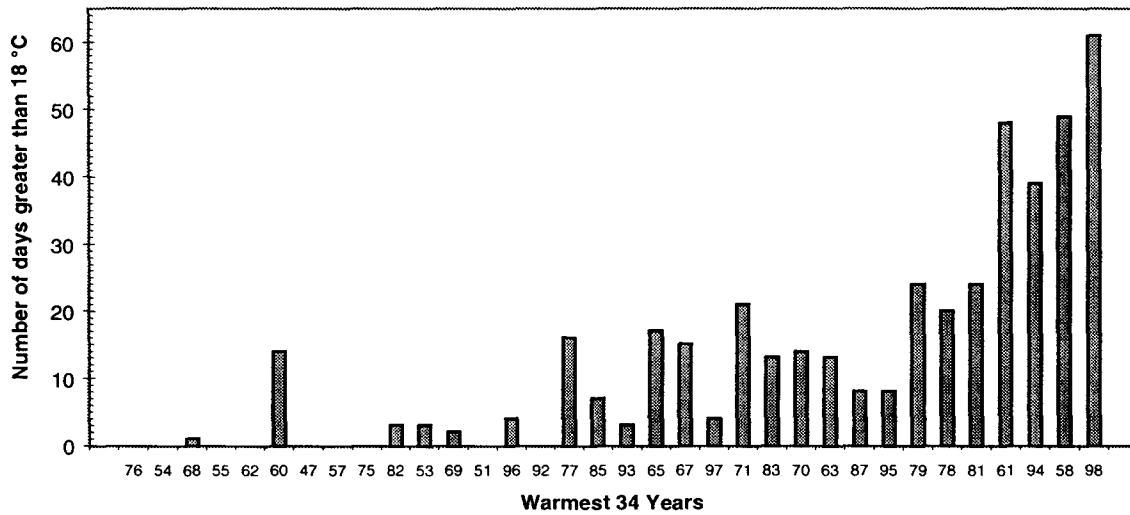


Fig. 5a and b. Mean summer temperature (a) and number of days greater than 18°C (b) at Hells Gate ranked for the warmest 34 years since 1941. Temperatures were collected between July 1 and September 15. Years with more than 10 days of missing temperature data were omitted.

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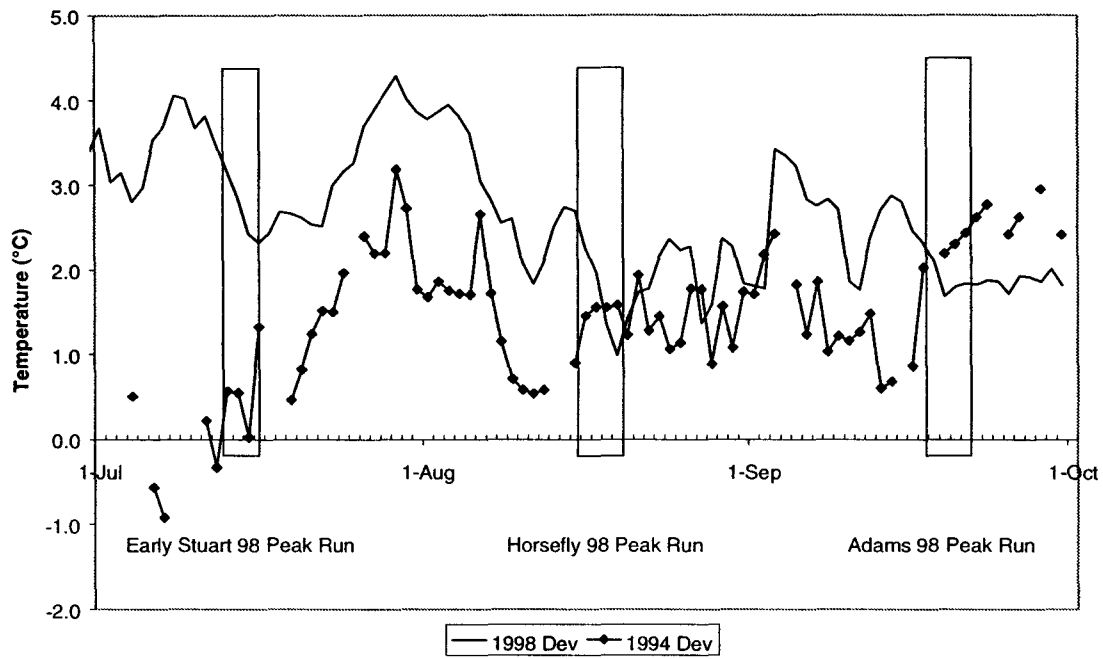
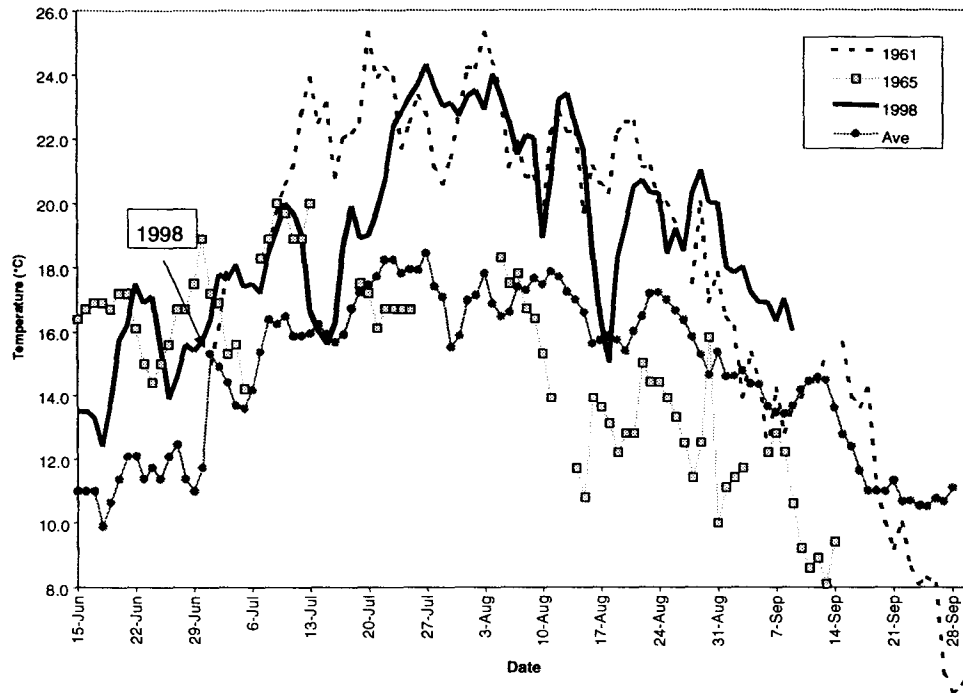


Fig. 6. Deviations in 1994 and 1998 water temperature at Hells Gate, from mean temperatures since 1941. Estimates of mean run timing at Hells Gate for three major spawning runs since 1978 are indicated.

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a).



b).

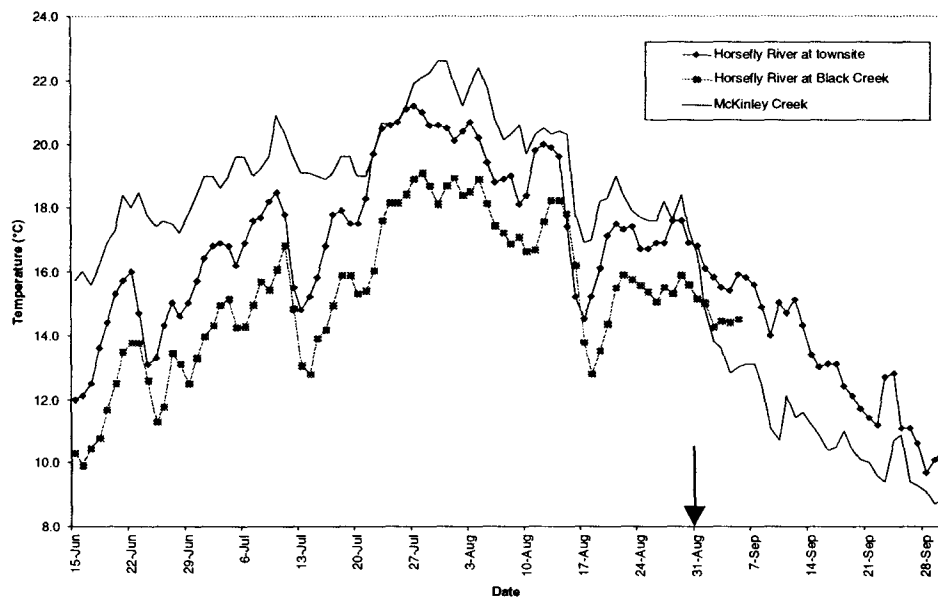


Fig. 7a and b. Maximum daily water temperature in the Horsefly River near the townsite (a). The average is calculated from temperatures in 1969, 1977, 1987, 1988, 1995, and 1996. Later temperatures from several sites in the Horsefly watershed are provided (b) to indicate the influence of the McKinley Lake siphon that was activated on August 31st in 1998 (arrow).

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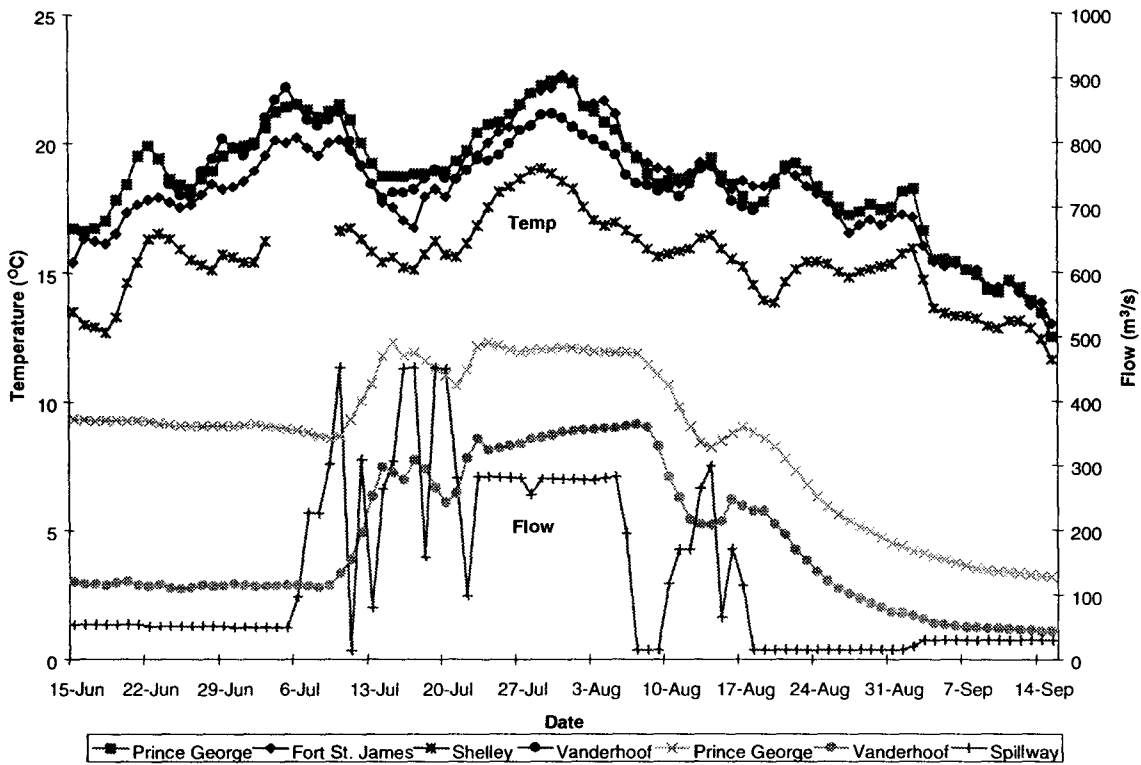


Fig. 8. Mean daily water temperatures of the Nechako River at Prince George and Vanderhoof (above the confluence with the Stuart River), the Stuart River below Fort St. James, and the Fraser River at Shelley. Also included are mean daily flows for the Nechako River at Vanderhoof, the Nechako River at Prince George, and the Skins Lake Spillway.

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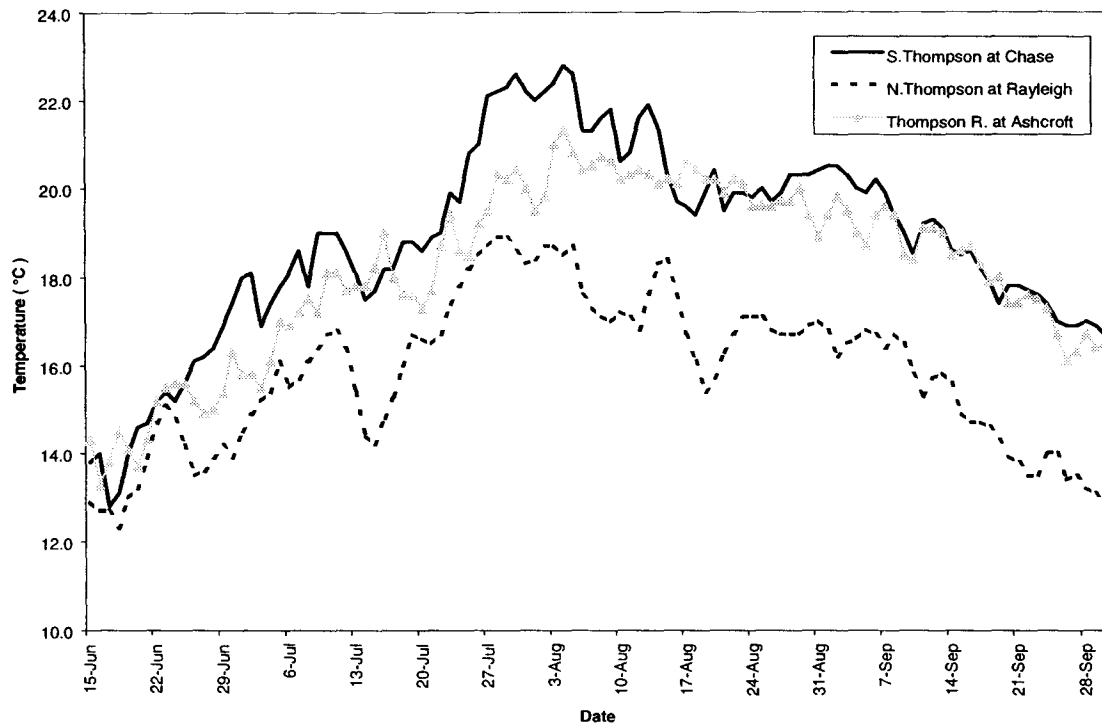


Fig. 9. Mean daily water temperatures in 1998 from the South Thompson River at Chase, the North Thompson at Rayleigh, and the Thompson River at Ashcroft.

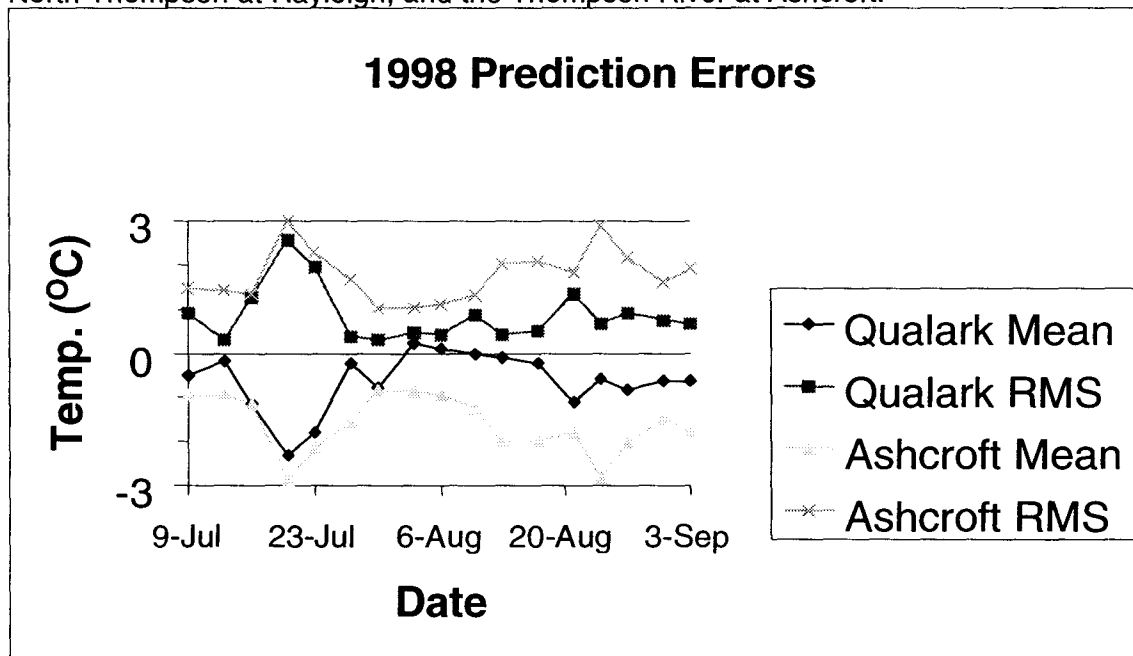


Fig. 10. Mean and root mean square (RMS) forecast errors for the river temperature model at Qualark Creek and Ashcroft.

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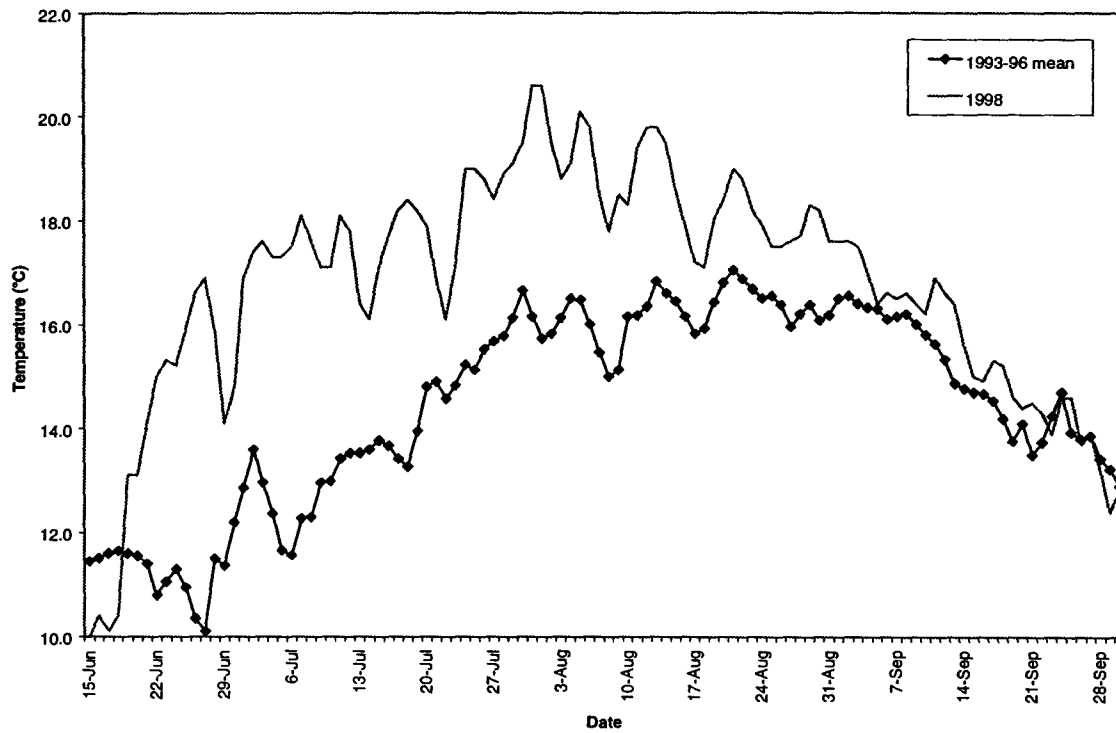


Fig. 11. Mean daily water temperatures from the Quesnel River in 1998. Averages are from years 1993 to 1996.

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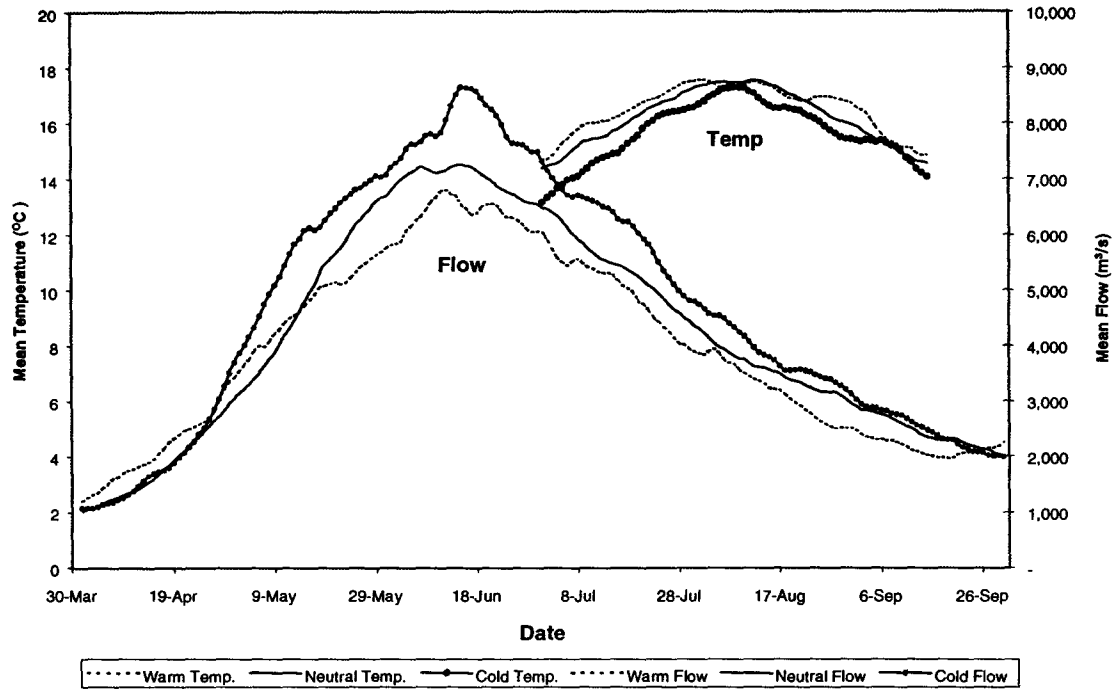


Fig. 12. Fraser River temperatures at Hells Gate and flows at Hope for the summers following warm (El Niño), cold (La Niña), and neutral Pacific Ocean events.

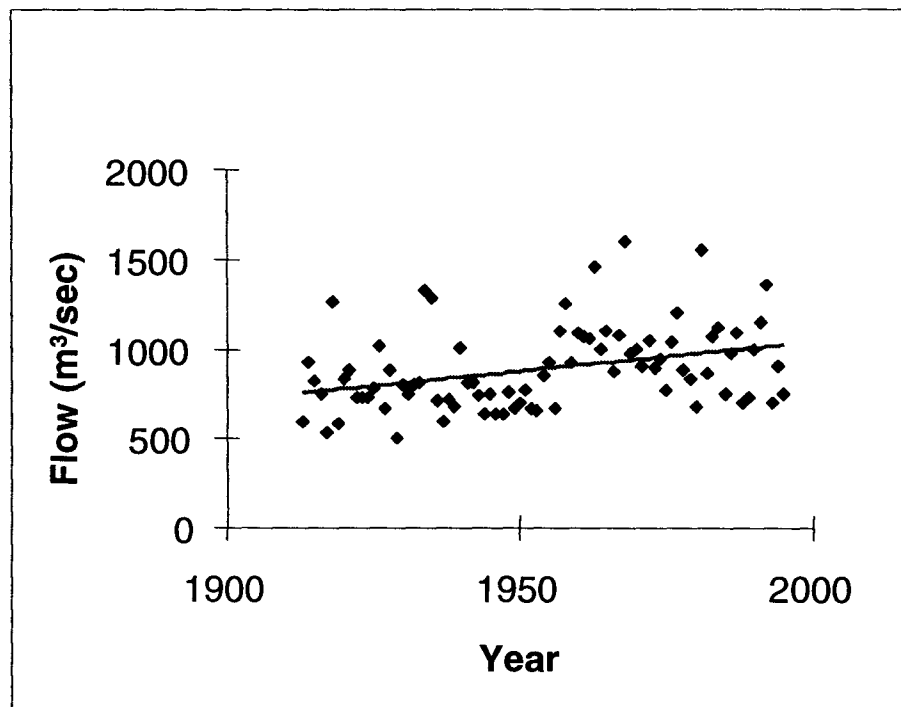


Fig. 13. Winter (January – March) Fraser River mean flows at Hope and the optimal linear trend.

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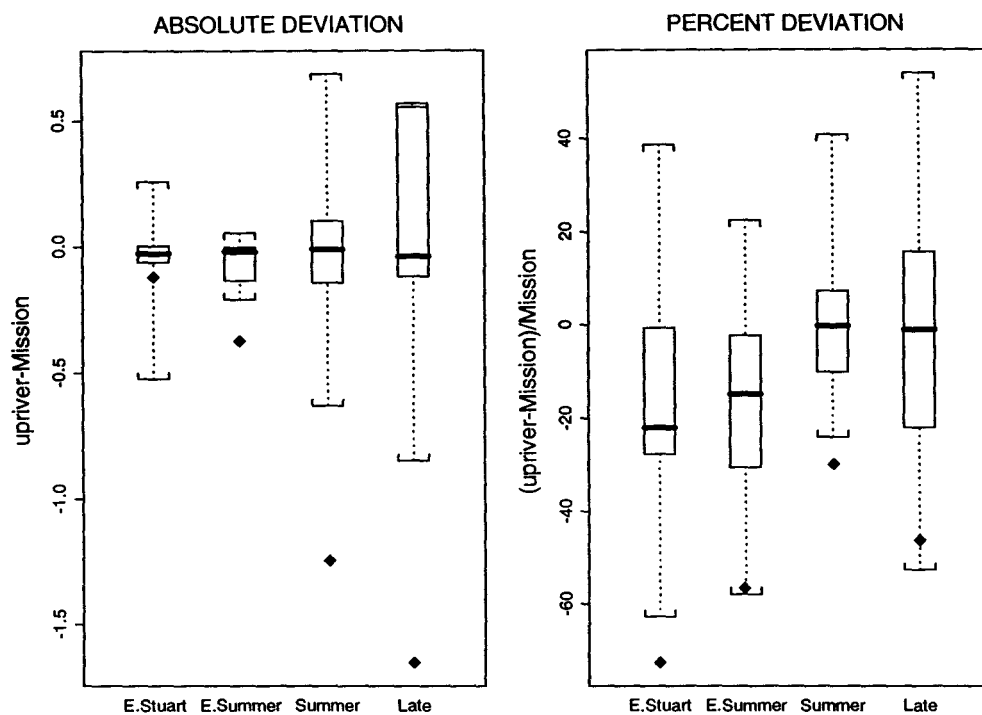


Fig. 14. Box plots of the absolute and percent deviation between sockeye hydroacoustic estimates at Mission and the sum of up-river catch and spawning escapement (1977-1997). The box shows the mid-50% (quartiles) of the distribution. The dark horizontal line is the median of the distribution. The broken vertical line shows the range. The diamond symbol denotes the 1998 data point.

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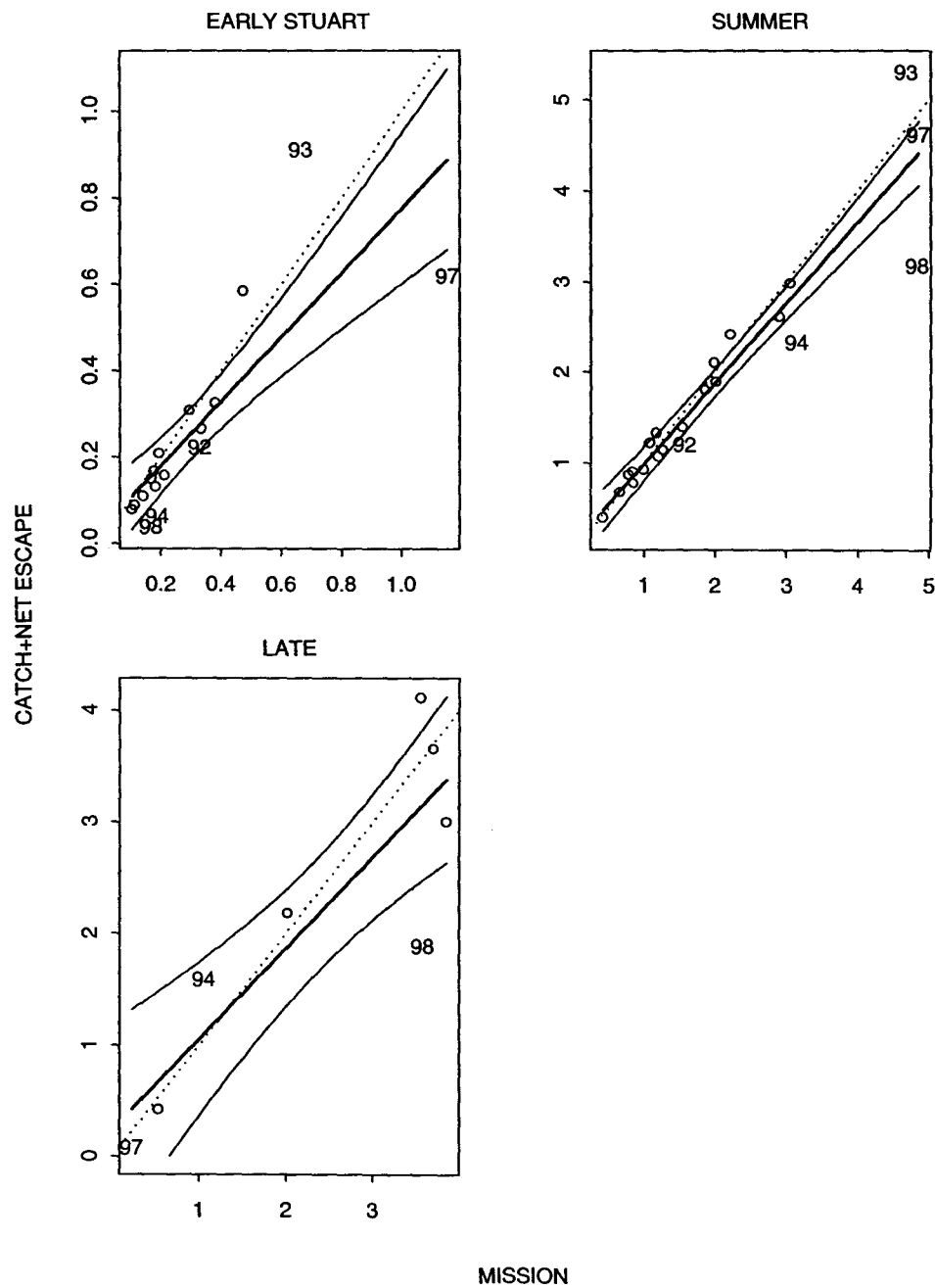


Fig. 15. Relationship between sockeye hydroacoustic estimates at Mission and the sum of up-river catch and spawning escapement. The broken line is the 1:1 line. The three solid lines are the 95% prediction intervals and best-fit linear regression for all years from 1977 to 1998.

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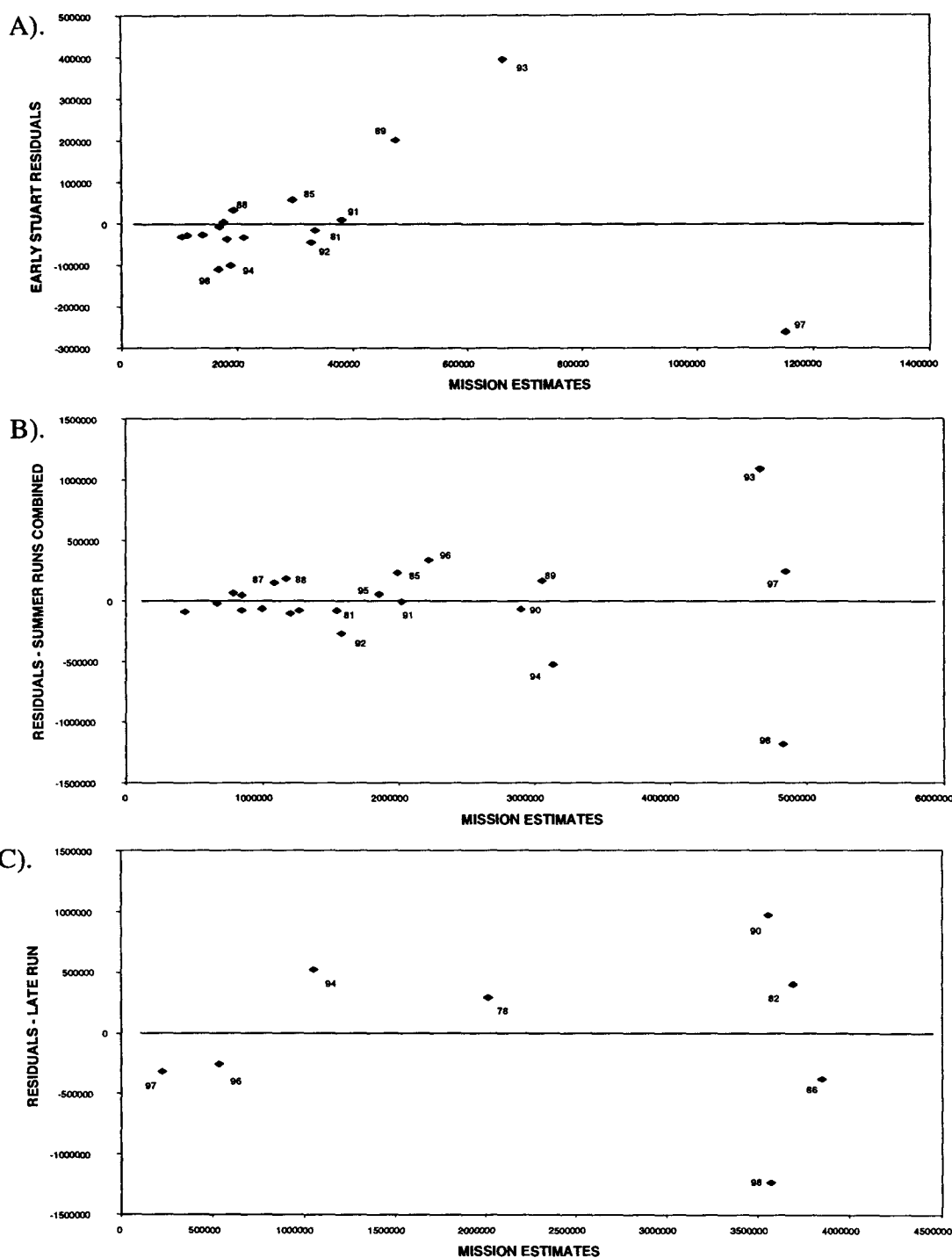


Fig. 16a, b, and c. Residuals from the relationship describing Mission run size and upstream net escapement estimates, plotted against run sizes from 1978 to 1998 for the (a) early Stuart run, (b) the combined summer runs, and (c) the late run.

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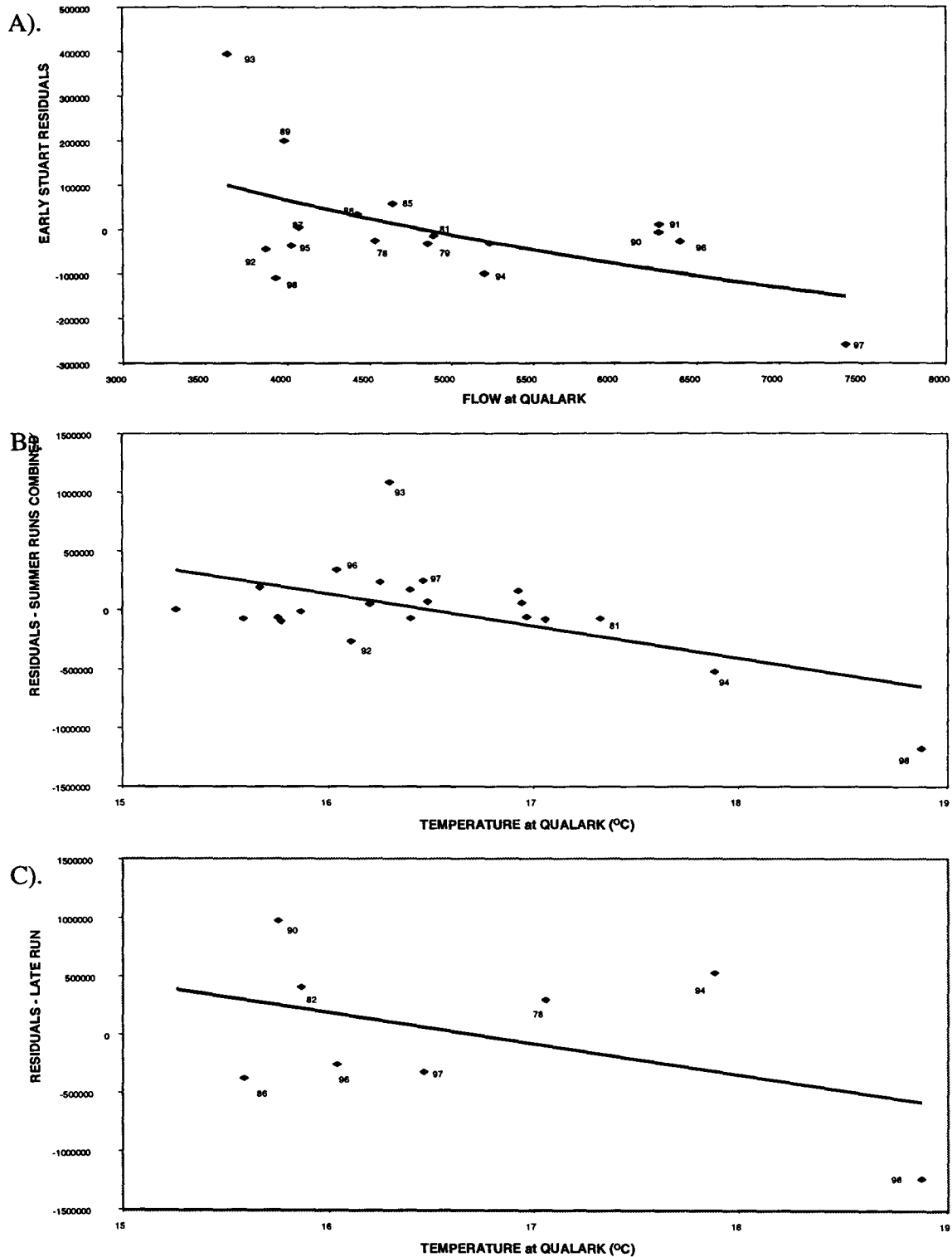


Fig. 17a, b, and c. Residuals from the relationship describing Mission run size and upstream net escapement estimates, plotted against mean July Fraser River discharge at Hope or the mean summer water temperature from Hells Gate from 1978 to 1998. Annual temperatures are ranked in Fig 5a. Plots are for the (a) early Stuart run, (b) the combined summer runs, and (c) the late run.

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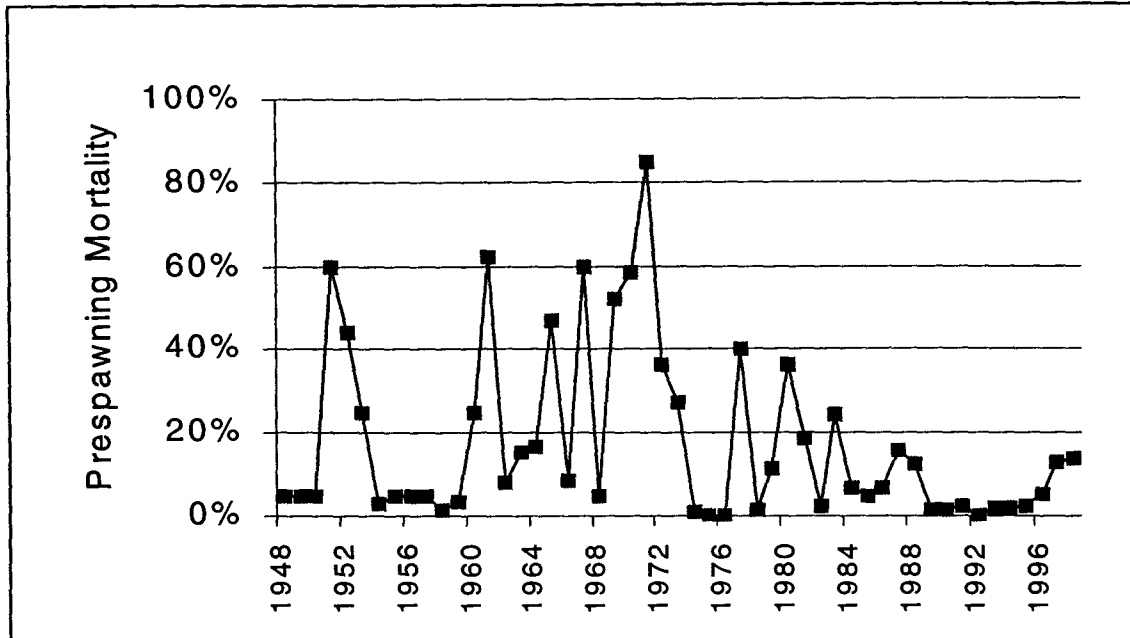


Fig. 18. Pre-spawning mortality (%) of Horsefly sockeye salmon from 1948 to 1998.

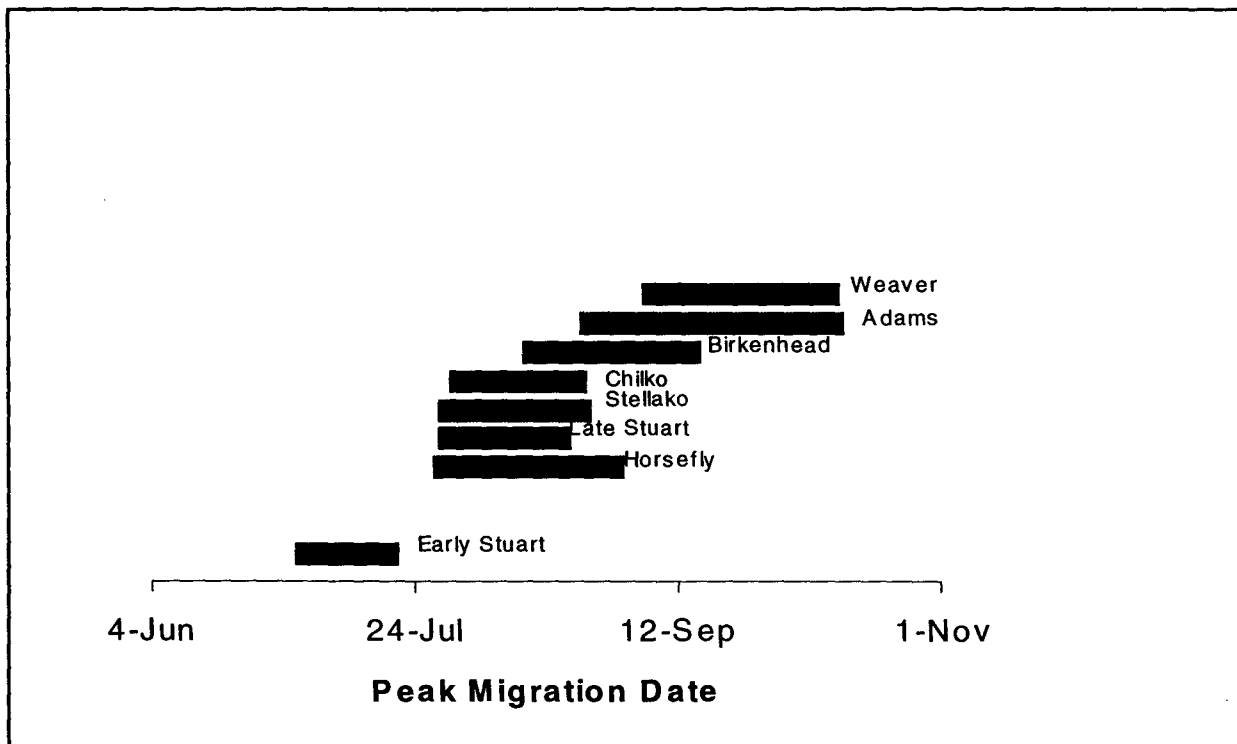


Fig. 19. Ranges in peak date of passage (e.g. 50% of run counted) past the Mission hydroacoustic facility for eight major Fraser River sockeye stocks from 1974 to 1998.

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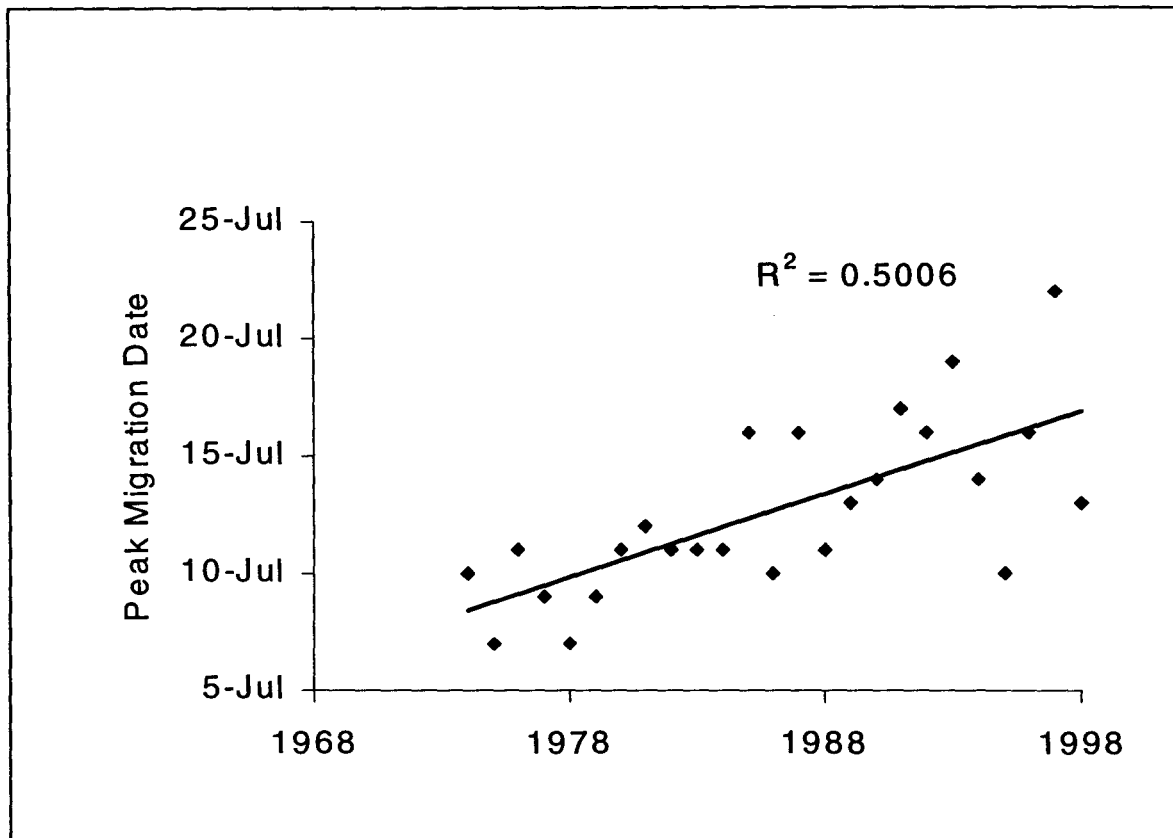


Fig. 20. Trend in peak date of passage of early Stuart sockeye past Hells Gate from 1974 to 1998 assuming a 4-day travel time from the Mission hydroacoustic facility to Hells Gate.

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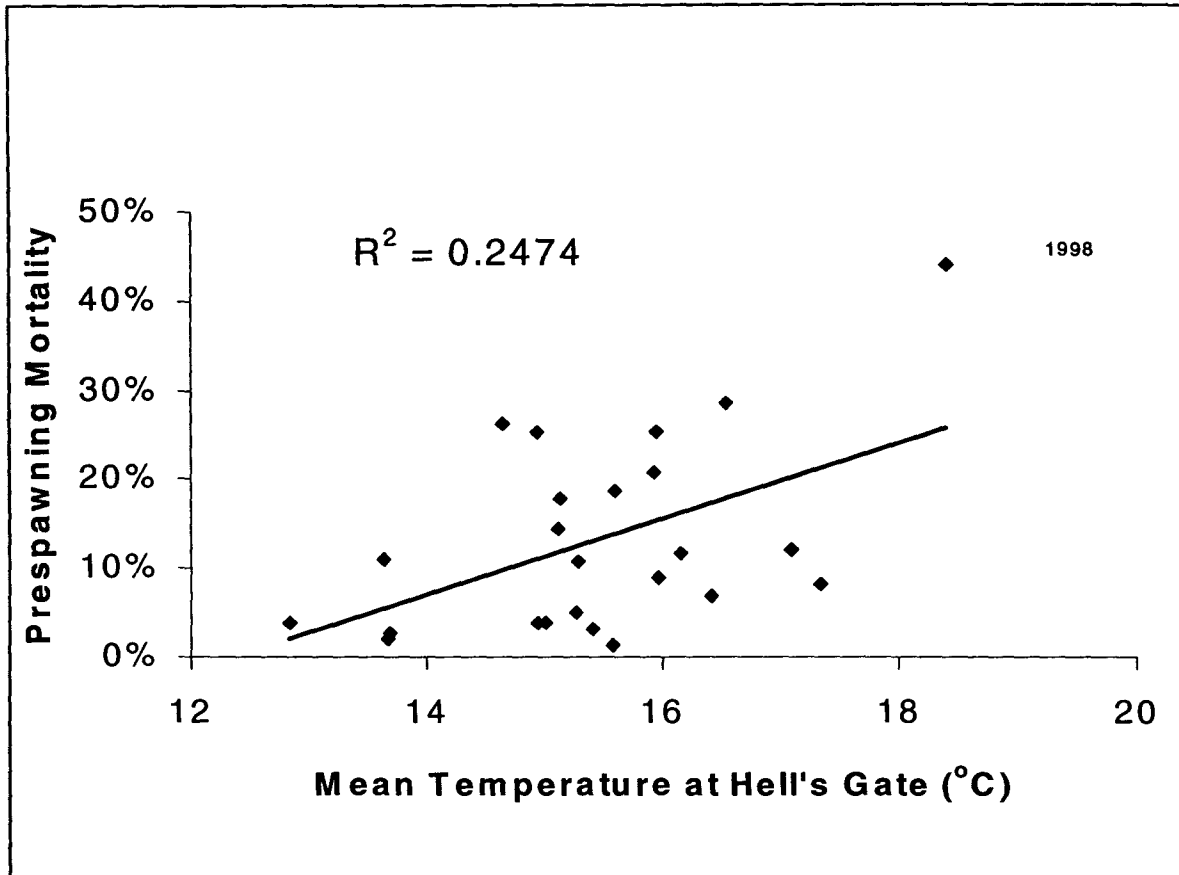


Fig. 21. Relationship between mean water temperature at Hells Gate (weighted by daily escapement) experienced by Early Stuart sockeye during passage and pre-spawning mortality from 1974 to 1998.

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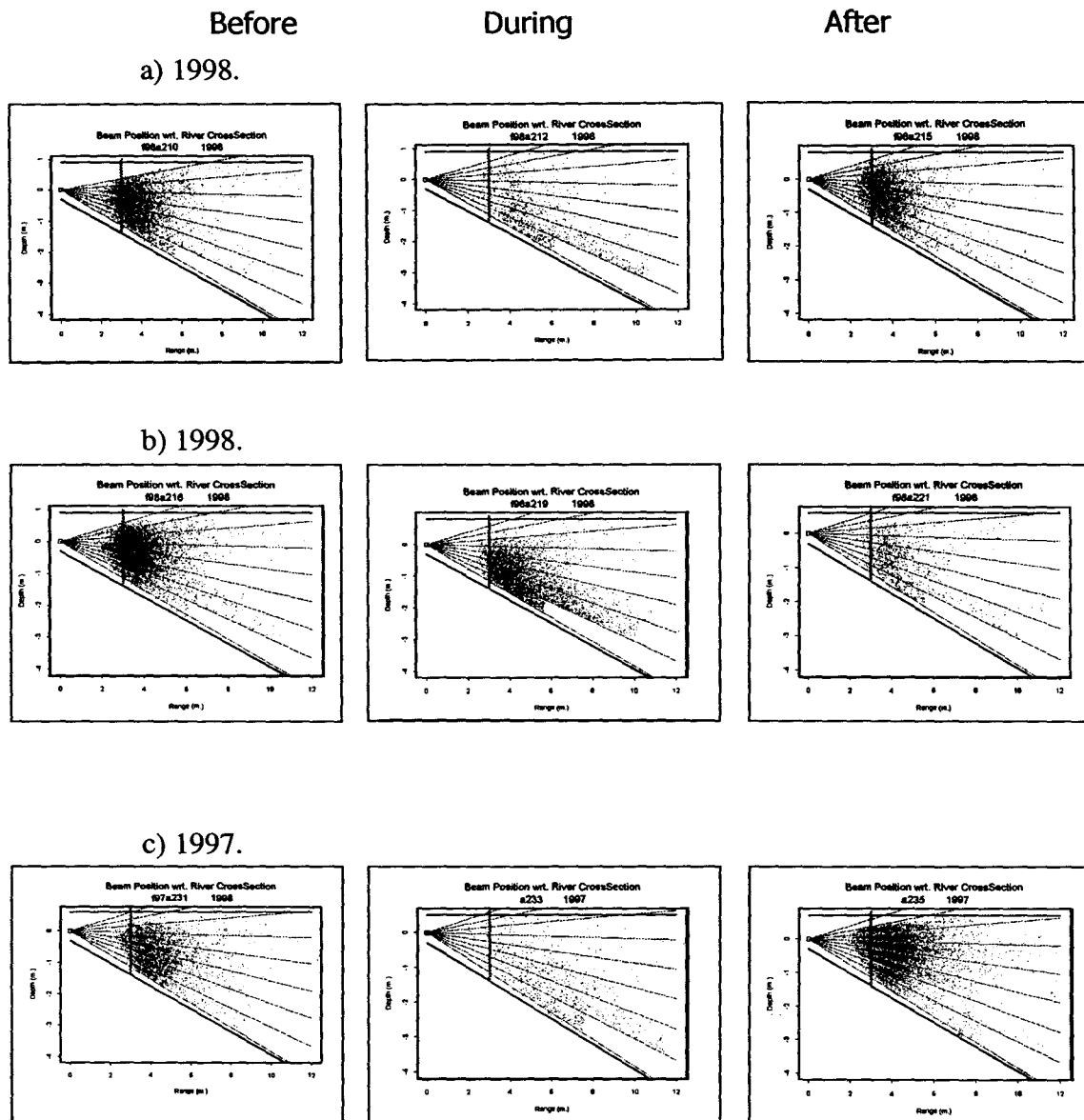
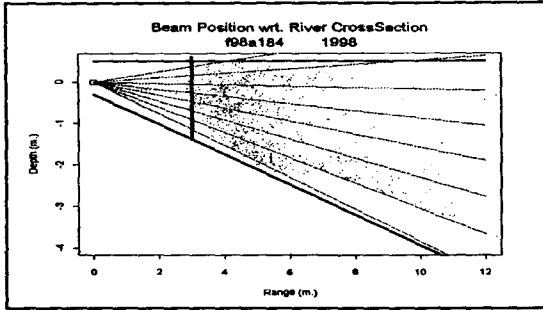


Fig. 22. Daily fan plots of fish passage detected at Qualark Creek for 3 Julian days (a, b, c) in 1997 and 1998. Each time sequence shows the distribution before, during, and after the gillnet fishing period. Each fan plot represents a composite of all transducer positions in the water column delineated with radiating lines. The solid vertical line represents the end of the fish detection weir.

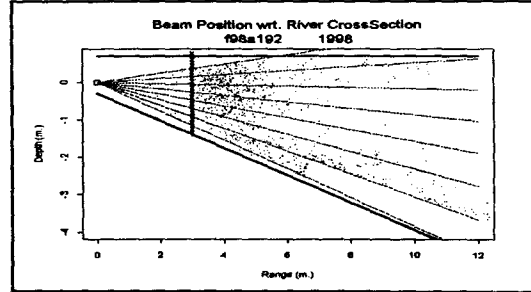
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a) 1998.

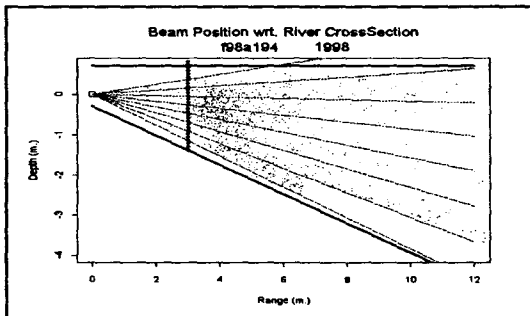
Normal



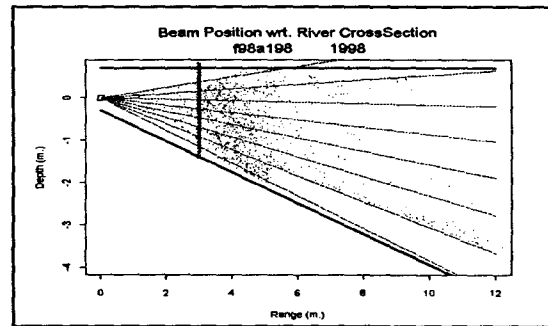
High



High

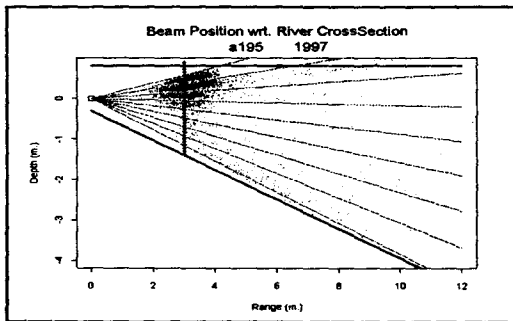


Normal



b) 1997.

High



Normal

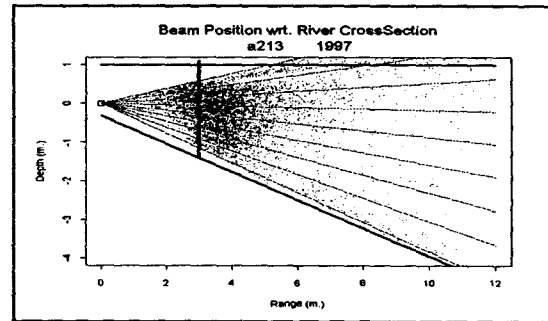
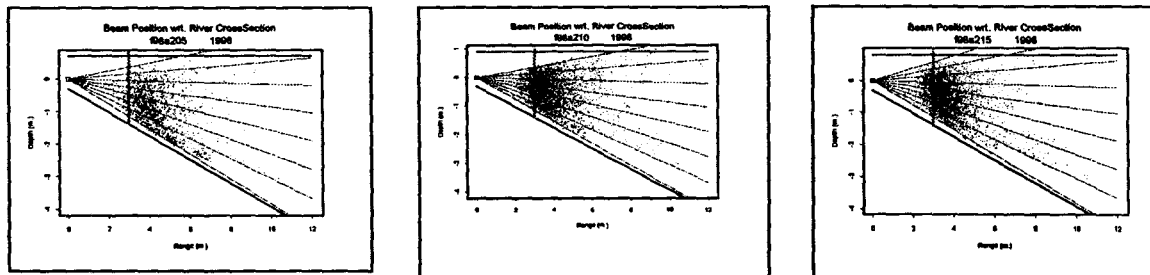


Fig. 23. Daily fan plots of fish passage detected at Qualark Creek in response to increases and decreases in river discharge in July, 1998 (a - low discharge year) and July, 1997 (b - high discharge year). Movement towards the surface when water discharge increases or away from the surface as the water discharge declines is demonstrated particularly well during 1997 when water discharge was very high. Each fan plot represents a composite of all transducer positions in the water column delineated with radiating lines. The solid vertical line represents the end of the fish detection weir.

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a) 1998.



b) 1997.

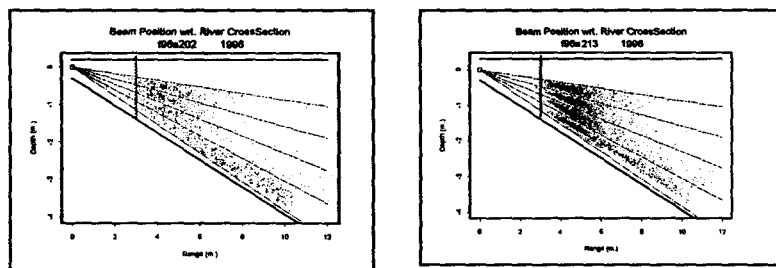


Fig. 24. Daily fan plots of fish passage detected at Qualark Creek for selected Julian days during two periods of increasing water temperature in 1998 (a) and 1996 (b). Temperatures in 1996 rose from 15.2°C to 18.4°C and from 18°C to greater than 19°C in 1998. Each fan plot represents a composite of all transducer positions in the water column delineated with radiating lines. The solid vertical line represents the end of the fish detection weir.

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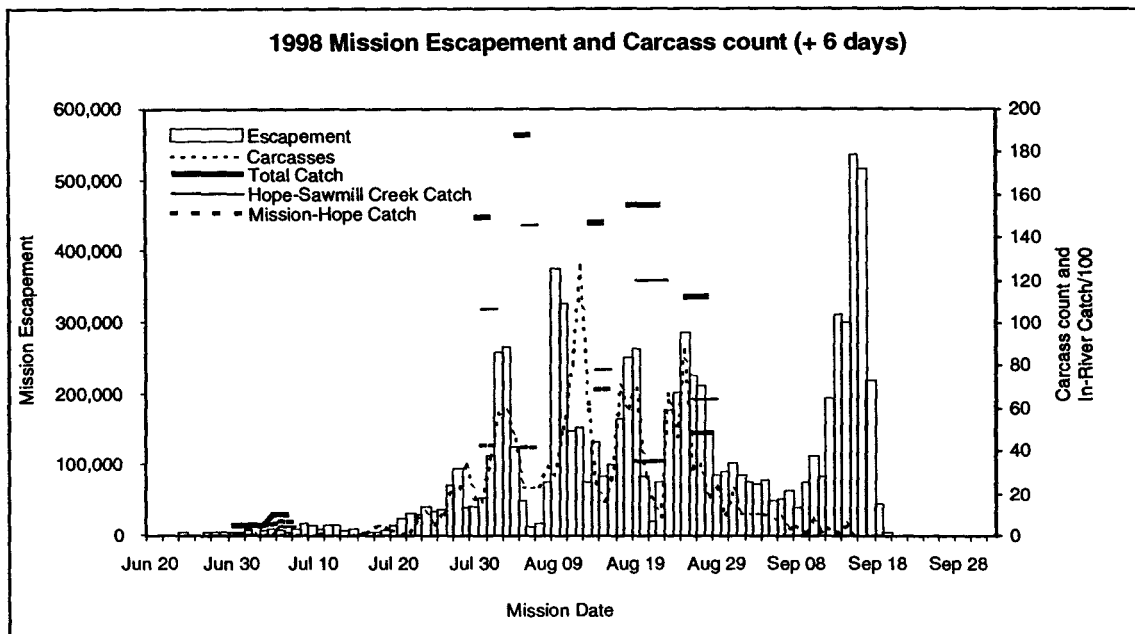


Fig. 25. Mission run timing and floating sockeye carcass counts for the 1998 sockeye season, with in-river fishery openings listed for two locations. Carcass counts assume a 6-day lag time (observations less 6 days) to account for time to death past Mission, and return drift.

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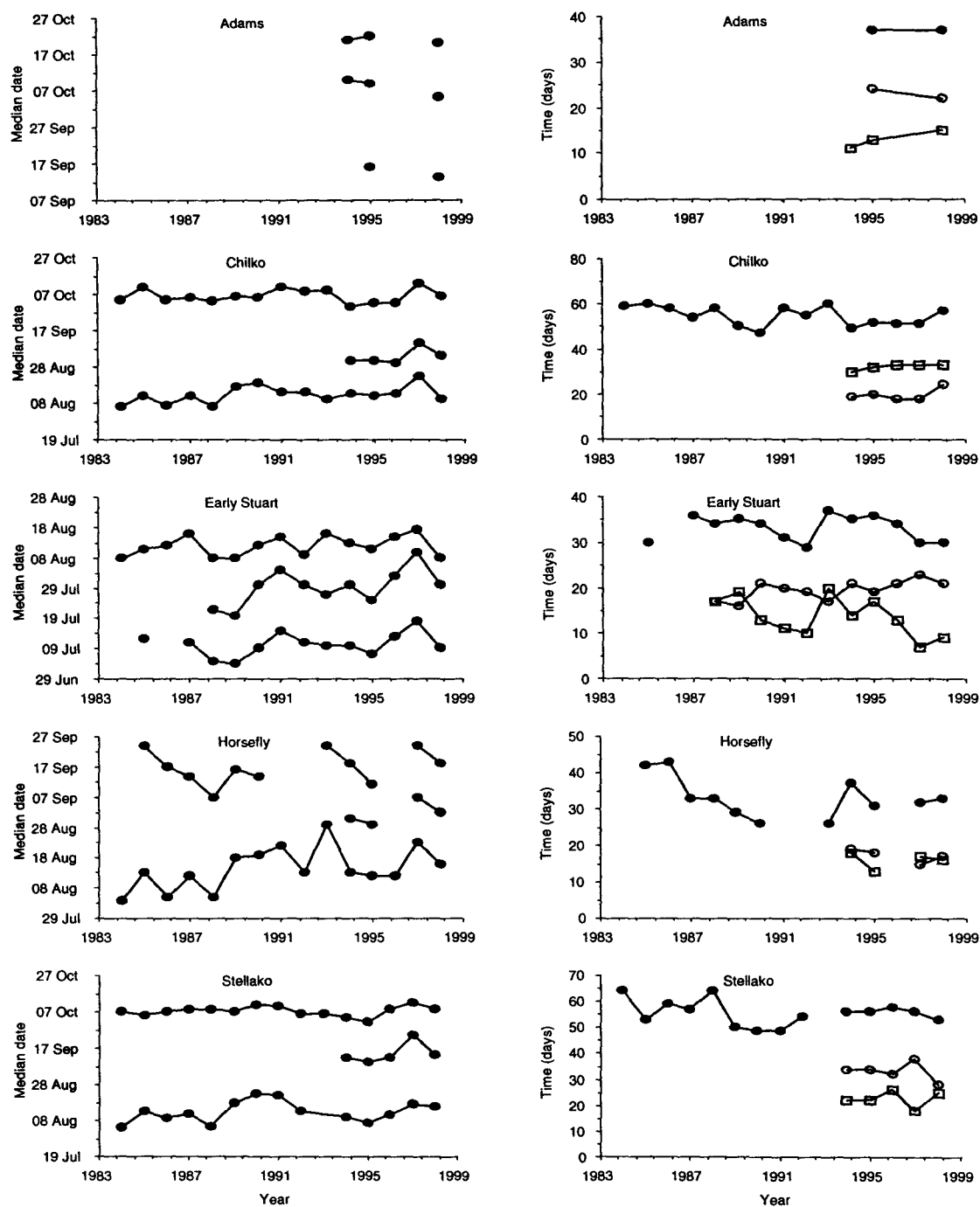


Fig. 26. Timing of freshwater events, across years, for five stocks. Graphs on the left show the median dates of sockeye migration past the Mission hydroacoustic site (bottom line), arrival at the spawning area (middle line) and carcass recovery (top line). Graphs on the right show the transit time from Mission to the spawning area (O's), the spawning life span (squares), and the sum of these (top line).

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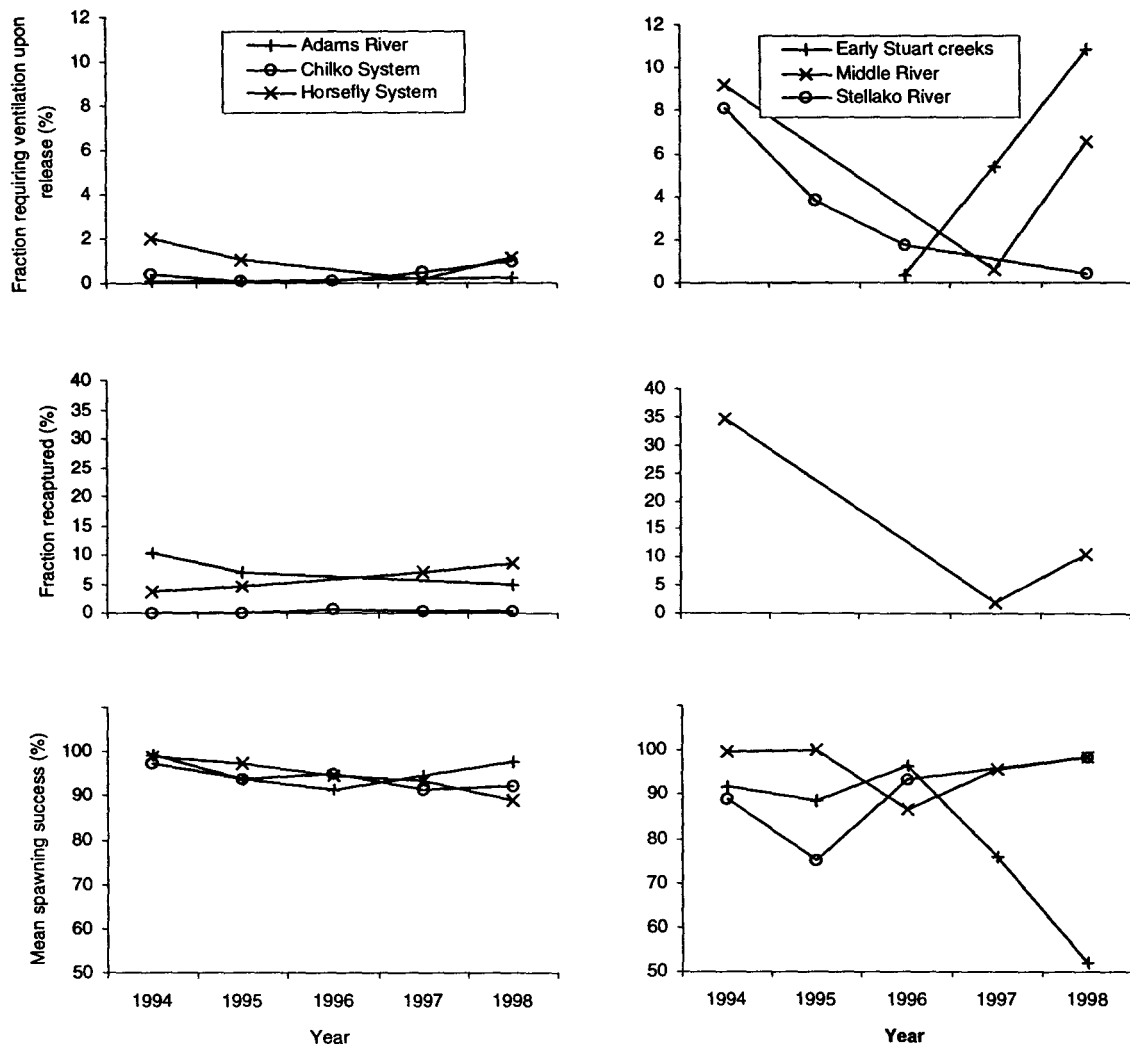


Fig. 27. Condition indicators versus year for 1994 to 1998 for six stocks: Left graphs - Adams, Chilko, and Horsefly stocks; Right graphs - early Stuart (Forfar, Gluskie, and Kynoch creeks, combined), Middle River, and Stellako stocks.

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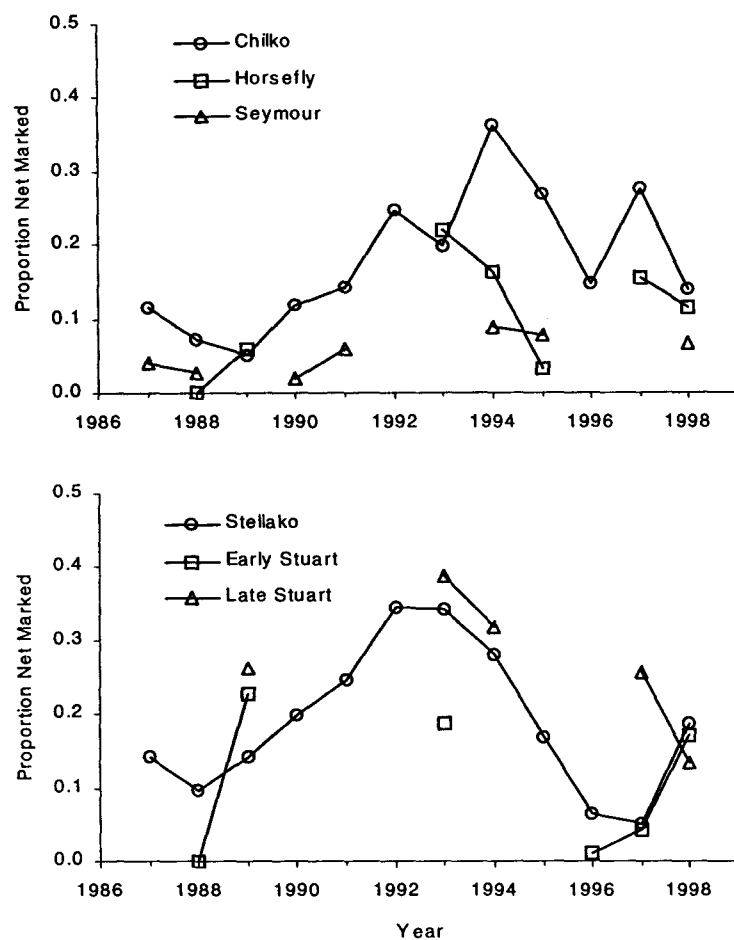


Fig. 28. Net mark incidence among sockeye examined upon arrival at the spawning areas (during tagging for mark-recapture studies) for six stocks (late Stuart values are the combined values of Middle River and Tachie stocks) for available years since 1987.

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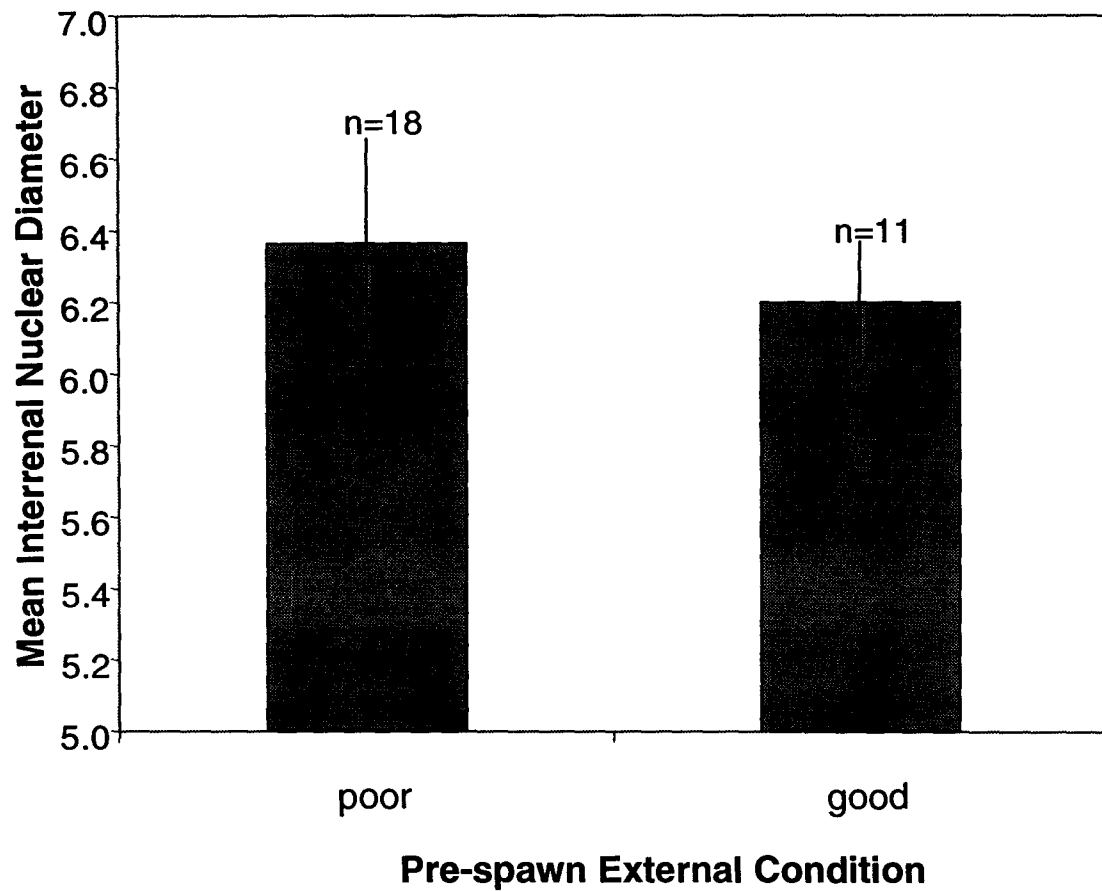


Fig. 29. Interrenal nuclear diameters from sockeye salmon recently arrived on the Horsefly River spawning grounds. Fish are categorized as being in good or poor condition based on external features and behaviour. Sample size (n) and two S.E.'s (vertical bars) of the mean are provided.

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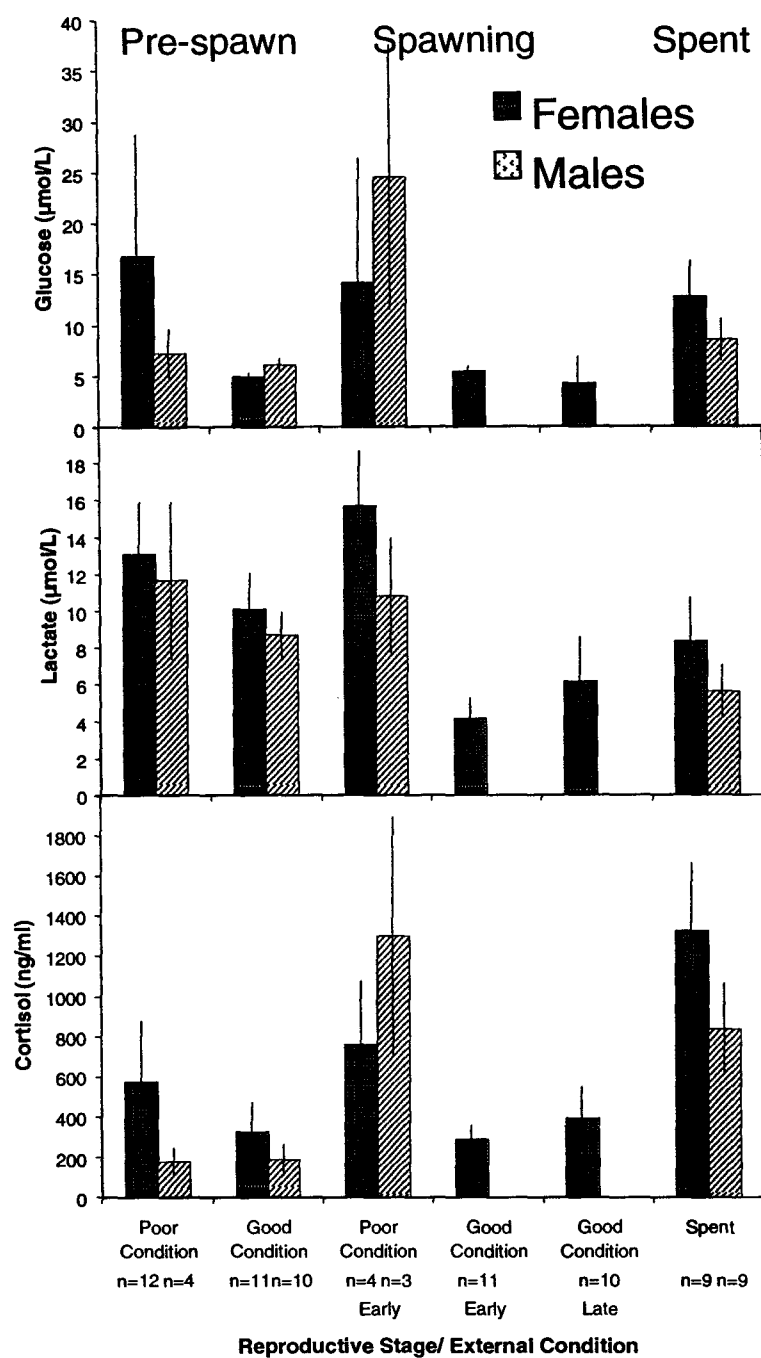


Fig. 30. Stress parameter measurements for male and female Horsefly sockeye salmon in three different reproductive stages and two different conditions. Pre-spawn fish were collected approximately 50 km from the spawning grounds. Condition of fish was determined from external features and behaviour. Two standard errors of the mean (vertical bars) and sample size (n) are also indicated.

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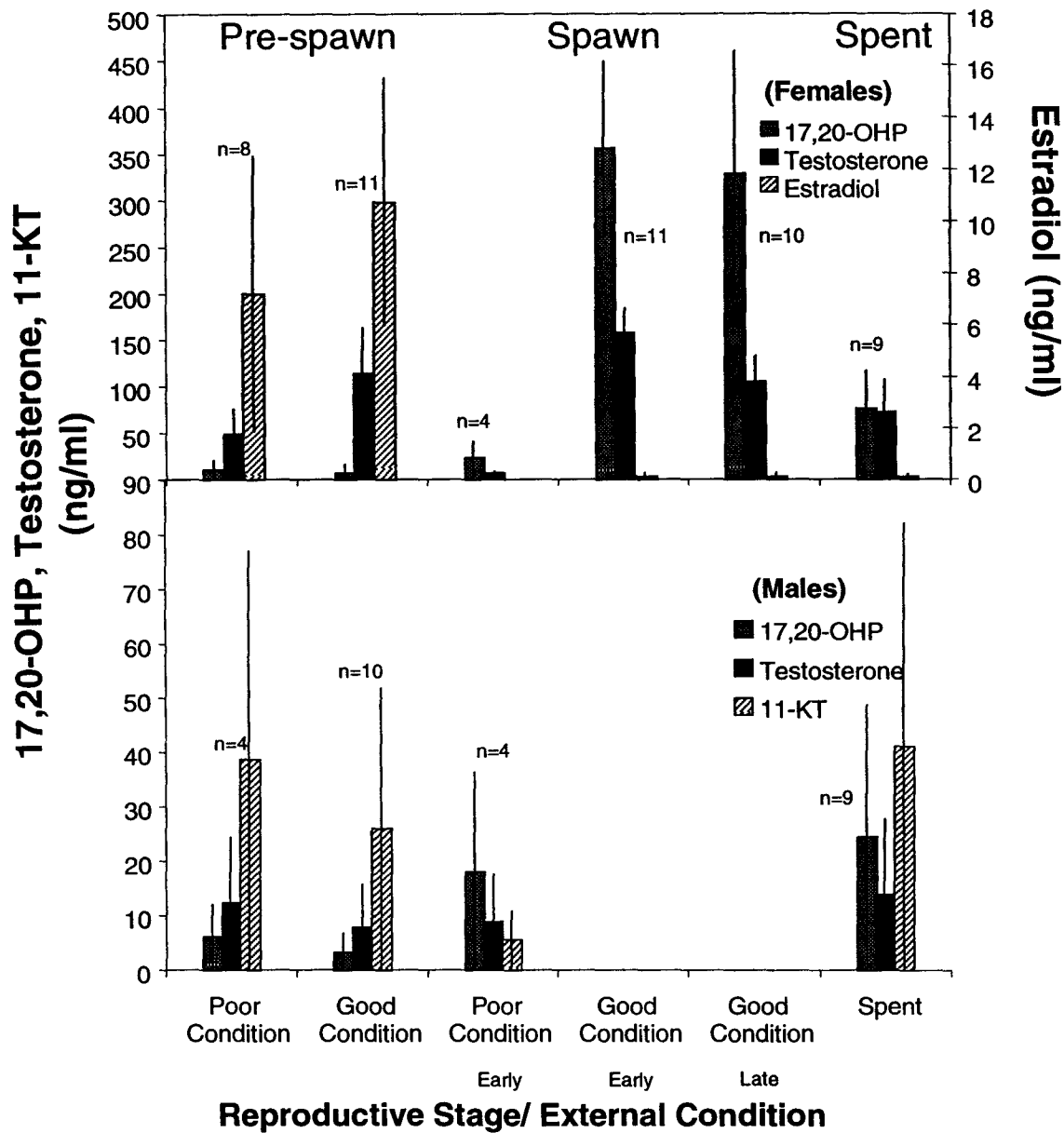


Fig. 31. Reproductive parameter measurements for male and female Horsefly sockeye salmon in three different reproductive stages and two different conditions. Pre-spawn fish were collected approximately 50 km from the spawning grounds. Condition of fish was determined from external features and behaviour. Two standard errors of the mean (vertical bars) and sample size (n) are also indicated.

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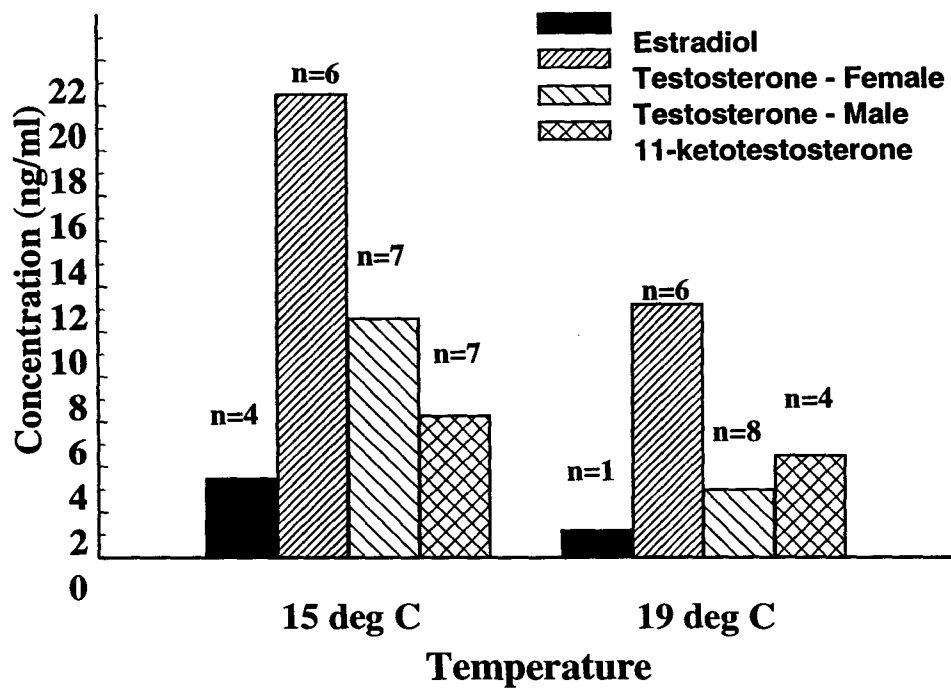


Fig. 32. Plasma sex hormone concentrations in early Stuart sockeye salmon held at 15°C or 19°C in the laboratory for 2 weeks (W.C. Clarke, personal communication). Sample size is provided (n).

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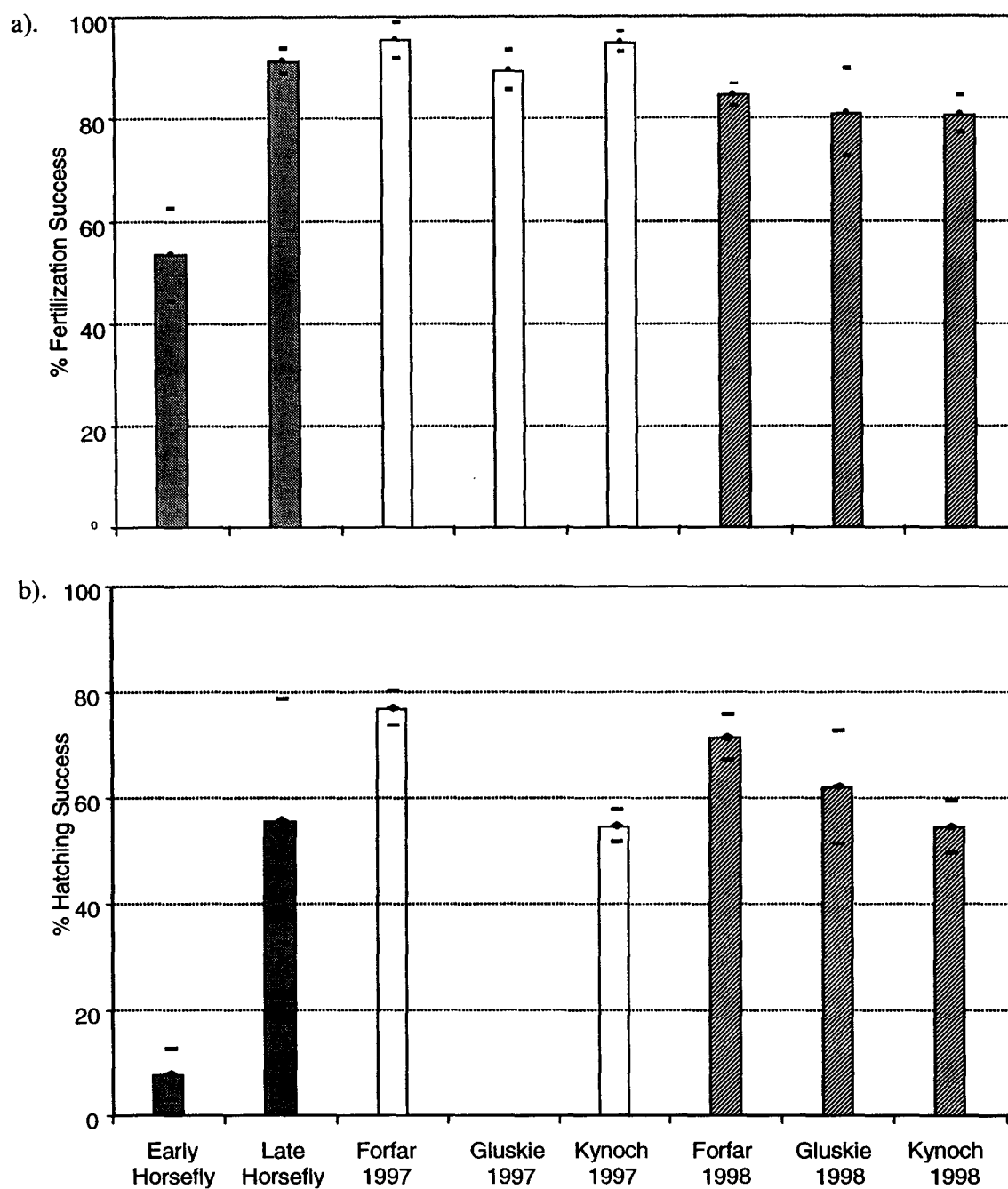


Fig. 33a and b. Fertilization success (a) and hatching success (b) of eggs from Horsefly and early Stuart (Forfar, Gluskie, Kynoch creeks) stocks of sockeye salmon in 1997 and 1998. Horsefly eggs were fertilized on September 3rd (early) and September 15th (late).

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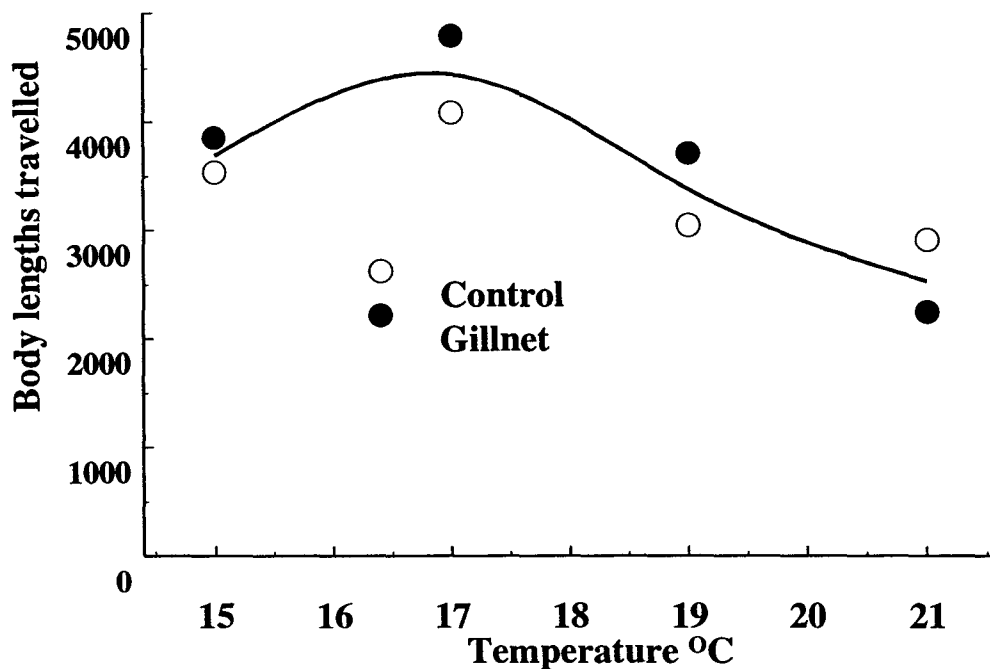


Fig. 34. Effect of acclimation temperature on distance swum by early Stuart sockeye salmon subjected to a swimming endurance test with either no prior stress (controls) or a 1-h gillnet entanglement stress.

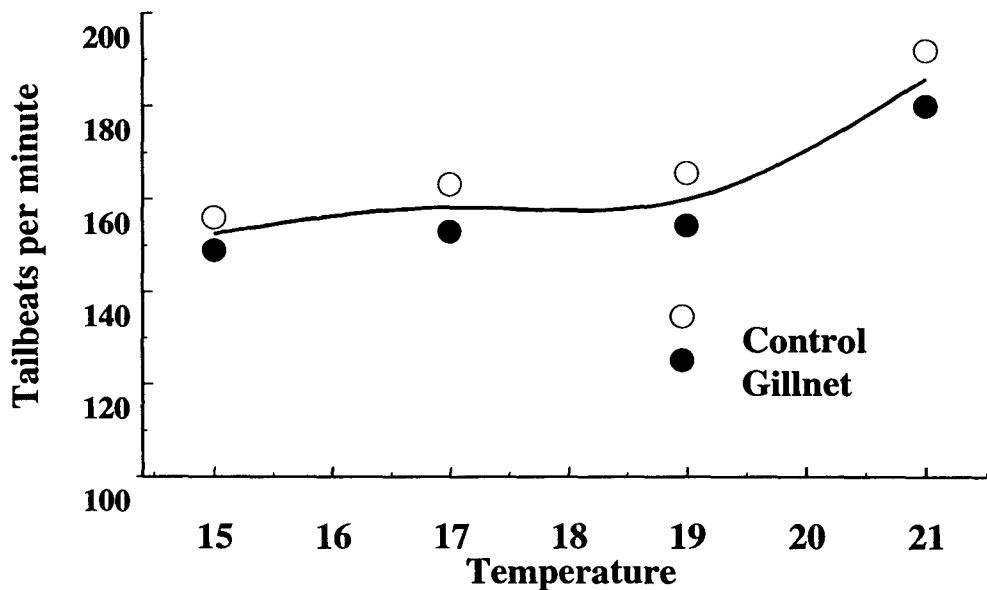


Fig. 35. Tail beat frequency for sockeye salmon at an imposed velocity of 70 cm/sec in relation to acclimation temperature for fish with either no prior stress (controls) or a 1-h gillnet entanglement stress.

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APPENDICES

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APPENDIX A. Mean daily water temperatures at real time logger sites, 1998.

Date	Qualark	Ashcroft	South Thompson	North Thompson	Chilcotin	Quesnel	Horsefly	Nechako	Stuart	Shelley
15-Jun	15.2	14.3	13.8	12.9	10.5	10.0	12.0	16.7	15.4	13.5
16-Jun	14.7	13.3	14.0	12.7	10.9	10.3	12.1	16.6	16.3	13.0
17-Jun	14.7	13.8	12.8	12.7	11.2	10.1	12.5	16.7	16.2	12.9
18-Jun	14.7	14.5	13.1	12.3	11.4	10.3	13.6	17.0	16.1	12.7
19-Jun	15.0	14.1	14.0	13.0	11.9	13.0	14.4	17.8	16.5	13.3
20-Jun	15.0	13.7	14.6	13.2	12.3	13.1	15.3	18.4	17.3	14.6
21-Jun	15.1	14.3	14.7	13.9	13.1	14.1	15.7	19.5	17.6	15.4
22-Jun	15.9	15.2	15.2	14.7	13.5	15.0	16.0	19.9	17.8	16.3
23-Jun	16.5	15.5	15.4	15.1	13.5	15.3	14.7	19.4	17.9	16.5
24-Jun	16.9	15.6	15.2	14.8	13.2	15.1	13.1	18.6	17.7	16.3
25-Jun	16.8	15.6	15.6	14.2	13.2	15.9	13.3	18.4	17.5	15.9
26-Jun	16.5	15.2	16.1	13.5	13.1	16.6	14.3	18.2	17.6	15.5
27-Jun	16.3	14.9	16.2	13.6	13.4	16.8	15.0	18.6	18.0	15.3
28-Jun	16.8	15.0	16.4	13.9	13.7	16.0	14.6	18.9	18.4	15.1
29-Jun	16.9	15.4	16.9	14.2	13.7	14.1	15.0	19.5	18.2	15.7
30-Jun	17.1	16.3	17.4	13.9	13.4	14.7	15.7	19.8	18.3	15.6
1-Jul	17.4	15.8	18.0	14.5	13.6	16.9	16.4	19.9	18.5	15.4
2-Jul	17.1	15.8	18.1	14.9	13.9	17.4	16.8	20.0	18.9	15.4
3-Jul	17.4	15.5	16.9	15.2	13.4	17.6	16.9	20.6	19.5	16.2
4-Jul	17.3	16.1	17.4	15.4	13.4	17.3	16.8	21.2	20.1	
5-Jul	17.6	17.0	17.8	16.1	14.6	17.3	16.2	21.4	20.0	
6-Jul	18.1	16.9	18.1	15.5	15.0	17.5	16.9	21.5	20.2	
7-Jul	18.6	17.2	18.6	15.7	15.2	18.0	17.6	21.3	19.8	
8-Jul	19.1	17.5	17.8	16.1	15.0	17.6	17.7	21.0	19.5	
9-Jul	19.2	17.2	19.0	16.4	15.3	17.0	18.2	21.2	20.0	
10-Jul	18.9	18.1	19.0	16.7	16.1	17.1	18.5	21.5	20.1	16.6
11-Jul	19.1	18.1	19.0	16.8	15.8	18.1	17.8	20.9	19.7	16.7
12-Jul	18.8	17.7	18.6	16.4	15.1	17.8	15.5	20.0	19.1	16.3
13-Jul	18.6	17.8	18.1	15.4	14.1	16.4	14.8	19.2	18.4	15.8
14-Jul	18.3	17.8	17.5	14.4	13.8	16.1	15.2	18.7	17.7	15.4
Date	Qualark	Ashcroft	South Thompson	North Thompson	Chilcotin	Quesnel	Horsefly	Nechako	Stuart	Shelley
15-Jul	18.0	18.2	17.7	14.2	14.2	17.1	15.8	18.7	17.5	15.6
16-Jul	18.0	19.0	18.2	14.8	14.4	17.7	16.8	18.7	17.0	15.2
17-Jul	18.4	18.0	18.2	15.3	15.3	18.1	17.8	18.8	16.7	15.1
18-Jul	18.5	17.6	18.8	16.0	15.3	18.4	17.9	18.8	17.9	15.7
19-Jul	18.7	17.6	18.8	16.7	15.6	18.2	17.5	18.9	18.2	16.2
20-Jul	18.8	17.3	18.6	16.6	15.2	17.9	17.5	18.9	17.9	15.7
21-Jul	18.8	17.7	18.9	16.5	15.1	16.9	18.3	19.3	18.6	15.6
22-Jul	19.0	18.7	19.0	16.7	15.0	16.1	19.7	19.7	19.6	16.1
23-Jul	19.5	19.4	19.9	17.4	15.9	17.0	20.5	20.4	19.5	16.8
24-Jul	19.7	18.6	19.7	17.8	16.5	18.9	20.6	20.7	20.0	17.5
25-Jul	19.8	18.5	20.8	18.2	16.6	19.0	20.7	20.8	20.4	18.1
26-Jul	20.3	19.2	21.0	18.5	16.6	18.8	21.1	21.1	20.6	18.3
27-Jul	20.7	19.5	22.1	18.7	16.1	18.3	21.2	21.5	21.4	18.6
28-Jul	20.9	20.3	22.2	18.9	17.5	18.8	21.0	21.9	21.9	18.9
29-Jul	21.1	20.2	22.3	18.9	17.4	19.1	20.6	22.2	22.0	19.0
30-Jul	21.0	20.4	22.6	18.6	17.9	19.5	20.6	22.4	22.1	18.8
31-Jul	21.0	20.0	22.2	18.3	17.4	20.6	20.5	22.5	22.6	18.5
1-Aug	20.9	19.5	22.0	18.4	17.5	20.6	20.1	22.3	22.4	18.2
2-Aug	21.0	19.8	22.2	18.7	16.1	19.5	20.4	21.4	21.4	17.5
3-Aug	21.2	21.0	22.4	18.7	16.9	18.8	20.7	21.2	21.5	17.0
4-Aug	21.1	21.3	22.8	18.5	16.9	19.0	20.2	20.8	21.6	16.8
5-Aug	20.9	20.8	22.6	18.7	16.8	20.1	19.4	20.5	21.1	16.9
6-Aug	20.4	20.4	21.3	17.6	16.0	19.8	18.8	19.8	19.8	16.6
7-Aug	20.1	20.5	21.3	17.3	16.4	18.5	18.9	19.4	19.5	16.3
8-Aug	19.9	20.7	21.6	17.1	16.2	17.8	19.0	18.8	19.2	15.9
9-Aug	19.9	20.6	21.8	17.0	15.7	18.4	18.1	18.4	19.0	15.6
10-Aug	19.5	20.2	20.6	17.2	16.0	19.6	18.4	18.5	18.9	15.7
11-Aug	19.3	20.3	20.8	17.1	15.6	19.4	19.8	18.6	18.4	15.8

12-Aug	19.5	20.4	21.6	16.8	16.4	19.8	20.0	18.6	18.8	15.9
13-Aug	19.8	20.3	21.9	17.6	16.6	19.7	19.9	19.1	19.2	16.3
14-Aug	20.0	20.1	21.4	18.3	16.7	19.5	19.6	19.4	19.1	16.4
15-Aug	19.8	20.2	20.3	18.4	15.8	18.6	17.4	18.7	18.7	15.9
16-Aug	19.3	20.1	19.7	17.6	14.3	17.9	15.2	18.4	18.2	15.5
17-Aug	18.9	20.6	19.6	16.7	14.1	17.2	14.5	17.9	18.5	15.2
18-Aug	18.4	20.4	19.4	16.1	14.6	17.1	15.2	17.5	18.3	14.5
19-Aug	17.9	20.2	19.9	15.4	14.9	18.0	16.1	17.7	18.3	13.9
			South	North						
Date	Qualark	Ashcroft	Thompson	Thompson	Chilcotin	Quesnel	Horsefly	Nechako	Stuart	Shelley
20-Aug	18.2	20.2	20.4	15.7	15.4	18.4	17.1	18.4	18.6	13.8
21-Aug	18.3	19.9	19.5	16.3	15.6	19.0	17.5	19.1	18.9	14.6
22-Aug	18.5	20.2	19.9	16.7	15.6	18.8	17.3	19.2	18.7	15.1
23-Aug	18.7	20.1	19.9	17.1	15.4	18.2	17.4	18.9	18.3	15.4
24-Aug	18.8	19.6	19.8	17.1	15.4	17.9	16.7	18.3	18.0	15.4
25-Aug	18.6	19.6	20.0	17.1	15.1	17.5	16.7	17.9	17.7	15.3
26-Aug	18.5	19.6	19.7	16.8	14.9	17.4	16.9	17.5	17.2	15.0
27-Aug	18.6	19.7	19.9	16.7	14.7	17.6	16.9	17.2	16.5	14.8
28-Aug	18.6	19.7	20.3	16.7	14.8	17.7	17.6	17.3	16.8	15.0
29-Aug	18.6	20.0	20.3	16.7	15.3	18.3	17.6	17.6	17.0	15.1
30-Aug	18.6	19.4	20.3	16.9	15.2	18.2	16.9	17.4	16.8	15.2
31-Aug	18.6	18.9	20.4	17.0	15.5	17.6	16.8	17.5	17.1	15.3
1-Sep	18.6	19.4	20.5	16.8	15.8	17.6	16.1	18.1	17.2	15.7
2-Sep	18.6	19.8	20.5	16.2	15.5	17.6	15.8	18.2	17.1	15.9
3-Sep	18.8	19.5	20.3	16.5	14.8	17.5	15.5	16.6	16.0	14.7
4-Sep	18.7	19.0	20.0	16.6	14.7	17.0	15.4	15.5	15.4	13.6
5-Sep	18.4	18.7	19.9	16.8	14.4	16.4	15.9	15.5	15.2	13.4
6-Sep	18.1	19.4	20.2	16.7	15.0	16.6	15.8	15.4	15.3	13.3
7-Sep	17.9	19.6	19.9	16.4	14.6	16.5	15.6	15.1	15.1	13.3
8-Sep	17.8	19.4	19.4	16.7	13.6	16.6	14.9	14.9	15.1	13.2
9-Sep	17.5	18.5	19.0	16.5	13.1	16.4	14.0	14.3	14.4	12.9
10-Sep	16.7	18.4	18.5	15.8	12.9	16.2	15.0	14.2	14.4	12.8
11-Sep	16.5	19.1	19.2	15.3	13.5	16.9	14.7	14.7	14.6	13.1
12-Sep	16.9	19.1	19.3	15.7	13.6	16.6	15.1	14.4	14.2	13.1
13-Sep	17.0	19.0	19.1	15.8	13.7	16.5	14.3	13.9	13.7	12.8
14-Sep	17.2	18.5	18.6	15.6	13.1	15.6	13.4	13.4	13.8	12.4
15-Sep	16.9	18.6	18.5	14.9	12.3	15.0	13.0	12.5	13.0	11.6
16-Sep	16.6	18.7	18.6	14.7	12.2	14.9	13.1	12.6	13.5	11.5
17-Sep	16.3	18.3	18.2	14.7	12.6	15.3	13.1	12.8	13.6	11.4
18-Sep	15.8	17.9	17.9	14.6	12.6	15.2	12.4	12.6	13.6	11.3
19-Sep	15.5	18.0	17.4	14.3	12.4	14.6	12.1	12.2	13.6	11.1
20-Sep	15.5	17.4	17.8	13.9	12.1	14.4	11.7	12.1	13.4	11.0
21-Sep	15.4	17.4	17.8	13.8	11.8	14.5	11.4	12.5	13.4	10.9
22-Sep	15.2	17.6	17.7	13.5	11.8	14.3	11.2	12.6	13.6	11.3
23-Sep	15.1	17.5	17.6	13.5	11.8	13.9	12.7	12.4	13.1	11.2
24-Sep	14.8	17.3	17.4	14.0	12.6	14.6	12.8	12.3	12.5	10.9
			South	North						
Date	Qualark	Ashcroft	Thompson	Thompson	Chilcotin	Quesnel	Horsefly	Nechako	Stuart	Shelley
25-Sep	14.9	16.7	17.0	14.0	12.2	14.7	11.1	12.0	12.5	10.9
26-Sep	14.8	16.1	16.9	13.4	10.7	13.7	11.1	11.5	12.8	10.6
27-Sep	14.5	16.3	16.9	13.5	11.6	13.9	10.6	11.7	13.0	10.6
28-Sep	14.4	16.7	17.0	13.2	10.8	13.2	9.7	11.3	12.7	10.4
29-Sep	14.4	16.4	16.9	13.1	10.2	12.4	10.1	10.7	12.4	10.1
30-Sep	14.4	16.5	16.7	12.8	10.6	12.8	10.4	11.1	12.4	10.1

APPENDIX B. Weekly summary of aerial, boat, and foot surveys made between June 29 and November 1 in the Fraser River watershed, including reported observations of unusual numbers of dead sockeye and unusual behaviour of migrating sockeye. Much of this information was gathered by questionnaire in April, 1999.

Date	Number of sockeye passing ^A	Surveyor category ^B	Type ^C	Number	Distance (km)	From	To	Observation	Usual # dead?	Call for info.
<i>Fraser River</i>										
Jun 29-5	52,400	F.O.	Boat	4	17	Sand Heads	Deas I.	Nothing unusual	1 or 2 per trip	Ian Mann/Herb Red (664-9250)
	52,400	F.O.	Boat	1	55	Alex Fraser	Mission	Nothing unusual	1 or 2 per trip	Scott Coultish (604-607-4160)
	43,600	F.O.	Boat	2	103	Mission	Sawmill Ck	Nothing unusual	<5 per trip	Glenn Kostiuik (604-826-3664)
	43,600	F.O.	Heli	1	103	Mission	Sawmill Ck	Nothing unusual		Glenn Kostiuik (604-826-3664)
	24,700	F.O.	Heli	1	38	Sawmill Ck	Boston Bar	Nothing unusual		Glenn Kostiuik (604-826-3664)
	24,700	F.O.	Boat	2	43	Boston Bar	Lytton	Nothing unusual	<6 per trip	Stu Cartwright (250-851-4922)
	4,500	F.O.	Boat	3 ^D	-	Lytton	Pr. George	Nothing unusual	1 or 2 per trip	Dennis Girodat (250-992-2434)
Jul 6-12	87,000	F.O.	Boat	6	17	Sand Heads	Deas I.	Nothing unusual	1 or 2 per trip	Ian Mann/Herb Red (664-9251)
	87,000	F.O.	Boat	4	55	Alex Fraser	Mission	Nothing unusual	1 or 2 per trip	Scott Coultish (604-607-4160)
	70,643	F.O.	Boat	13	103	Mission	Sawmill Ck	Nothing unusual	<5 per trip	Glenn Kostiuik (604-826-3664)
	70,643	F.O.	Heli	4	103	Mission	Sawmill Ck	Nothing unusual		
	53,743	F.O.	Heli	4	38	Sawmill Ck	Boston Bar	Nothing unusual		
	53,743	F.O.	Boat	1	43	Boston Bar	Lytton	Nothing unusual	<6 per trip	Stu Cartwright (250-851-4923)
	24,800	A.F.M.	Foot	2	-	Lillooet	Pavillion Ck	Nothing unusual		Natalie Vivian
Jul 13-19	24,800	F.O.	Boat	3 ^D	-	Lytton	Pr. George	Nothing unusual	1 or 2 per trip	Dennis Girodat (250-992-2434)
	45,900	F.O.	Boat	9	17	Sand Heads	Deas I.	Nothing unusual	1 or 2 per trip	Ian Mann/Herb Red (664-9252)
	45,900	F.O.	Boat	2	55	Alex Fraser	Mission	Nothing unusual	1 or 2 per trip	Scott Coultish (604-607-4160)
	63,356	F.O.	Boat	6	103	Mission	Sawmill Ck	Nothing unusual	<5 per trip	Glenn Kostiuik (604-826-3664)
	63,356	F.O.	Heli	1	103	Mission	Sawmill Ck	Nothing unusual		
	88,676	A.F.M.	Foot	1	-	Siska site		Nothing unusual		Natalie Vivian

	88,676	F.O.	Heli	1	38	Sawmill Ck	Boston Bar	Nothing unusual		
	88,676	F.O.	Boat	1	43	Boston Bar	Lytton	Nothing unusual	<6 per trip	Stu Cartwright (250-851-4924)
	59,039	A.F.M.	Foot	2	-	Lillooet	Pavillion Ck	Nothing unusual		Natalie Vivian
	59,039	F.O.	Boat	3 ^D	-	Lytton	Pr. George	Nothing unusual	1 or 2 per trip	Dennis Girodat (250-992-2434)
Jul 20-26	258,600	F.O.	Boat	7	17	Sand Heads	Deas I.	Nothing unusual	1 or 2 per trip	Ian Mann/Herb Red (664-9253)
	258,600	F.O.	Boat	6	55	Alex Fraser	Mission	Nothing unusual	1 or 2 per trip	Scott Coultish (604- 607-4160)
	139,188	F.O.	Boat	2	103	Mission	Sawmill Ck	Nothing unusual	<5 per trip	Glenn Kostiuk (604- 826-3664)
	83,303	A.F.M.	-	1	-	Stoner Ck		Moribund sockeye		
	83,303	F.O.	Boat	3 ^D	-	Lytton	Pr. George	Nothing unusual	1 or 2 per trip	Dennis Girodat (250-992-2434)

Fraser River

Jul 27-2	866,000	F.O.	Boat	1	17	Sand Heads	Deas I.	Nothing unusual	1 or 2 per trip	IanMann/Herb Red (664-9254)
	866,000	F.O.	Boat	2	55	Alex Fraser	Mission	Nothing unusual	1 or 2 per trip	Scott Coultish (604- 607-4160)
	356,420	A.F.M.	Heli	3	103	Mission	Sawmill Ck	Nothing unusual		Terry Robertson
	356,420	F.O.	Boat	4	103	Mission	Sawmill Ck	Nothing unusual	<5 per trip	Glenn Kostiuk (604- 826-3664)
	356,420	F.O.	Heli	1	103	Mission	Sawmill Ck	Nothing unusual		
	320,443	A.F.M.	Boat	1	54	Hell's Gate	Lytton	Nothing unusual		Natalie Vivian
	320,443	F.O.	Heli	1	38	Sawmill Ck	Boston Bar	Nothing unusual		
	320,443	F.O.	Boat	1	43	Boston Bar	Lytton	Nothing unusual	<6 per trip	Stu Cartwright (250-851-4926)
	37,116	A.F.M.	Foot	1	-	Lillooet	Pavillion Ck	5 dead floating out of Bridge River		Natalie Vivian
	37,116	A.F.M.	Boat	1	19	Lytton	Texas Ck	Nothing unusual		
	37,116	A.F.M.	-	1	-	Stoner Ck		Sockeye holding		
	37,116	F.O.	Boat	3 ^D	-	Lytton	Pr. George	Nothing unusual	1 or 2 per trip	Dennis Girodat (250-992-2434)
Aug 3-9	983,000	F.O.	Boat	6	17	Sand Heads	Deas I.	Nothing unusual	1 or 2 per trip	Ian Mann/HerbRed (664-9255)
	983,000	F.O.	Boat	7	55	Alex Fraser	Mission	Nothing unusual	1 or 2 per trip	Scott Coultish (604- 607-4160)
	827,436	A.F.M.	Heli	3	103	Mission	Sawmill Ck	Nothing unusual		Terry Robertson
	827,436	C.P.	Boat	1	105	Haney	Hope	128 dead;		Gord Koster
	827,436	F.O.	Boat	1	103	Mission	Sawmill Ck	Nothing unusual	<5 per trip	Glenn Kostiuk (604- 826-3664)
	827,436	Qualark		1	-	Emory Ck		Sockeye holding		Qualark staff
	827,436	Sport	Foot	1	-	Near Chilliwack		50 dead downstream in 3 hrs		

883,146	A.F.M.	Boat	1	54	Hell's Gate	Lytton	"Lots of morts"		Natalie Vivian
883,146	F.O.	Boat	6	43	Boston Bar	Lytton	Nothing unusual	<6 per trip	Stu Cartwright (250-851-4927) Qualark staff
883,146	Qualark		1	-	Spuzzum Ck		Some holding		Natalie Vivian
133,489	A.F.M.	Foot	7	-	Kelly Creek		1 dead; "threw back scarred ones"		
133,489	A.F.M.	Boat	1	19	Lytton	Texas Ck	See Sawmill Ck. to Lytton		
133,489	A.F.M.	Foot	1	-	Churn Ck		Sockeye holding; some dead floating past		
133,489	F.O.	Boat	3 ⁰	-	Lytton	Pr. George	2 dead near Narcosli Ck/4 dead on beach below Cottonwood R.	1 or 2 per trip	Dennis Girodat (250-992-2434)

Fraser River

Aug 10-16	858,000	F.O.	Boat	5	17	Sand Heads	Deas I.	Nothing unusual	1 or 2 per trip	Ian Mann/HerbRed (664-9256)
	858,000	F.O.	Boat	4	55	Alex Fraser	Mission	Nothing unusual	1 or 2 per trip	Scott Coultish (604- 607-4160)
	1,249,730	A.F.M.	Heli	3	103	Mission	Sawmill Ck	Up to 100 dead		Terry Robertson
	1,249,730	C.P.	Boat	1	60	Mission	Jones Ck	18 dead and a dead accumulation on shore		Gord Koster
	1,249,730	F.O.	Boat	3	103	Mission	Sawmill Ck	Nothing unusual	<5 per trip	Glenn Kostiuk (604- 826-3664)
	1,249,730	F.O.	Heli	1	103	Mission	Sawmill Ck	Nothing unusual		
	1,249,730	F.O.	Heli	1	51	Aggasiz	Emory Ck	22 dead		F.O.'s
	1,249,730	Qualark		1	-	Emory Ck		100 moribund sockeye holding		Qualark staff
	1,249,730	STAD	Foot	1	-	Emory Ck		23 live, 1 dead		Lanny Kalnin
	983,016	A.F.M.	Boat	1	54	Hell's gate	Lytton	Two morts (good shape)		Natalie Vivian
	983,016	A.F.M.	Foot	1	-	Sawmill Ck	Lytton	"Fishers found one dead sockeye"		
	983,016	F.O.	Heli	1	38	Sawmill Ck	Boston Bar	Nothing unusual		
	983,016	F.O.	Boat	1	43	Boston Bar	Lytton	Nothing unusual	12 to 18	Stu Cartwright (250-851-4928) Lanny Kalnin
	983,016	STAD	Foot	1	-	Spuzzum Ck		20-30 holding, approx. 10 fungused; 4 old carcasses		
	521,069	A.F.M.	Foot	12	-	Kelly Ck		6 dead; 26 scarred sox thrown back		Natalie Vivian
	521,069	A.F.M.	Boat	1	19	Lytton	Texas Ck	See Sawmill Ck. to Lytton		
	521,069	F.O.	Boat	3 ⁰	-	Lytton	Pr. George	2 dead near Quesnel R	1 or 2 per trip	Dennis Girodat (250-992-2434)
Aug 17-23	1,073,500	F.O.	Boat	8	17	Sand Heads	Deas I.	Nothing unusual	1 or 2 per trip	Ian Mann/HerbRed (664-9257)
	1,073,500	F.O.	Boat	12	55	Alex Fraser	Mission	Nothing unusual	1 or 2 per trip	Scott Coultish (604- 607-4160)

APPENDIX C. Observations of chinook pre-spawning mortalities (PSM), 1992-1998, in the Fraser watershed.

It is generally thought chinook pre-spawning mortalities occur every year, especially in warm water years. As most chinook stocks in the interior are enumerated by two or three overflights annually due to size and relative inaccessibility, well documented numbers are generally not available. Exceptions to this are the systems with counting fences and dead pitch programs run by Fisheries and Oceans Canada and, most notably, the Thompson area monitored by the Shuswap Nation Fisheries Commission.

1992

Nechako River:

- app. 10 dead observed, all thought to be PSM. (B.Rosenberger, personal communication).

South Thompson River:

- app. 20-30 dead observed, all thought to be PSM (B.Rosenberger, personnel communication).

1994

Wide spread mortalities throughout the Fraser system, especially in Thompson River drainage. All observations by B. Rosenberger, except where noted.

Nicola River:

- higher than normal, possibly over 1,000 PSM. Water temperatures reached 28.5° C.

Thompson River:

- Many PSM observed in stretch between Kamloops Lake to Ashcroft.

Lower Shuswap River:

- est. 6,000 PSM. From a total estimated escapement of 16,000, this represents app. 38% of the population (Galesloot 1994). Tissue sample analysis by Fisheries and Oceans Canada revealed the presence of *Ichthyophthirius multifiliis* and fungal infections.

Finn Creek:

- est. 100 PSM. This represents app. 10% of female population (Galesloot 1994).

1995

Lower Shuswap River:

- 245 PSM recovered in dead pitch; this represents app. 20% of female population (Galesloot 1995).

Upper Adams River:

- No PSM observed (Galesloot 1995).

Bonaparte River:

- 11 PSM recovered in dead pitch; this represents app. 6.5% of female population (Galesloot 1995).

1996

Lower Shuswap River:

- 154 PSM recovered in dead pitch; this represents app. 3% of female population (Galesloot 1996).

Bonaparte River, Finn Creek, Louis Creek, and Raft River:

- No PSM observed (Galesloot 1996).

1997

Lower Shuswap River:

- 970 PSM recovered in dead pitch; this represents app. 22% of female population. (Galesloot, 1997).

Bonaparte River:

- 59 PSM recovered in dead pitch; this represents app. 33% of female population (Galesloot 1997).

1998

As in 1994, widespread PSM mortalities were reported throughout the Fraser River system, with the best documentation from the Thompson drainage.

Thompson River:

- up to 50 dead/ hour, unspawned chinook were observed floating past Spences Bridge on August 19. (R. Bailey, personal communication).
Maximum water temperature at Ashcroft on this date was 20.8° C.

South Thompson River:

- rough est. of app. 12,000 PSM which could represent 25% of the total population. A disease survey was conducted by Fisheries and Oceans Canada and reported as a severe infestation of the gills with *Dermocystidium*, a protozoan parasite, and *epitheliocystis*, a chlamydia-like organism. Conditions may have been exacerbated by low water levels, excessive number of returning fish, and high water temperatures. (S. St.-Hilaire and B. Rosenberger, personal communication).

Nicola River:

- much evidence (but little documentation) to suggest PSM was of major proportions, i.e., >50%; many carcasses on river banks consumed by predators, very low and warm water (maximum water temperatures between 20 and 22° for most of August).
- between Sept. 5 and 18, app. 1500-2000 chinook were observed off the mouth of the Nicola; only 300 actually entered the river (R. Bailey, personal communication).

Lower Shuswap River:

- large PSM, possibly up to 3,000 fish.

Nechako River:

- 1 reported dead, unspawned fish found Sept. 6 (R. Elson, personal communication).

Upper Fraser River:

- 2 reported dead, unspawned fish found late August (R. Elson, personal communication).

Bowron River (3), Chilako River (6), Stuart River (6), and Slim Creek (2):

- bracketed numbers indicate riverboat trips last summer. No dead fish were observed (B. Meisner, personal communication).